<u>**Working Paper No. 36/03**</u>

**Are Within-Season Rents Maximised
in an Open-Access Fishery?**

by

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*Centre for Fisheries Economics
Discussion paper No. 5/2003*

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Abstract

It is often assumed that zero rents are generated in an open-access fishery. There are many justifications for this, such as the existence of intraseasonal and interseasonal stock externalities, and entry and exit of vessels dependent on positive and negative rents. It is important to consider under what conditions the assumption applies, because these determine the benefits of different types of regulation, and the way in which open-access conditions are modelled.

Some of the conditions which determine whether within-season rents are maximised under open-access are examined for the simple condition under which all inputs of the fisher are variable. Fishers are modelled as non-cooperative decision makers. It is shown that depending on how the fisher's problem is formulated, there may be no dissipation of within-season rents, no matter what the number of fishers. Key decision variables investigated are the rate of fishing mortality over a fixed fishing season, the stock to fish stocks down to over a fishing season, and the length of the fishing season. A striking finding is that aggregate rent and end-of-season stock outcomes change radically when the length of fishing season is added to fishing mortality as a decision variable. It is shown that under open-access conditions aggregate rent may be maximised or dissipated for alternative but equally simple assumptions about the decision variables.

1) Introduction

Two quite different ways are used to characterise the rents generated over a harvesting season in discrete-time models of open-access fisheries. Under the first, perhaps more usual, method, fishing effort is applied to the extent that rents are fully or partially dissipated. Under the second method within-season rents are modelled as maximised with respect to effort. This paper considers the question of which approach is correct, or whether the question should really be under what conditions or assumptions is each approach correct.

In a recent paper Weitzman (2002) obtains the important result that if the goal of fishery regulators is to maximise economic efficiency under ecological uncertainty, taxes rather than quotas are the preferred instrument. The result is based on the assumption that the fishery, unregulated or regulated, behaves as a myopic rent maximiser for the usual case of unit cost of harvesting increasing with declining fish stock. Myopia stems from the inter-period incentive under open-access for each fisher to overharvest in the current period, because none can appropriate the full gain that otherwise would have accrued from future growth of stock saved from capture in the current period. Koenig (1984) refers to this as an interseasonal stock externality.

The assumption of current-period rent maximisation is open to question if no allowance is made for possible adverse within-period stock effects on the cost per fish caught. An adverse stock effect (or congestion effect, or intraseasonal stock externality) occurs if a fisher in expending an additional unit of fishing effort reduces stock which increases not only his or her cost per fish caught but the cost per fish caught of all other fishers. Too much will be caught if each fisher sets effort at the level which equates within-period marginal benefit with marginal private cost rather than marginal social cost.

Consistent with unit cost of harvesting increasing with declining stock, a Schaefer harvest function with a positive stock exponent is often used to model fishery effort at the level that average benefit equates with average cost, or the level at which rents are dissipated, for expository purposes (e.g., Munro and Scott, 1985; and Hartwick and Olewiler, 1986), and in numerical modelling, sometimes as a result of adjustment of effort over time a positive function of rents which are sub-maximal (e.g., Androkovich and Stollery, 1994; Brasao et al. 2000; Duarte et al. 2000; Kennedy 1999; and Knowler et al. 2001).

To provide some insight into the questions raised, three sole fisher and open-access cases are examined, differing by decision variables: a) fishing mortality as the decision variable applied over a fixed harvesting period; b) harvest or end-of–period stock as the decision variable; and c) harvesting period as the decision variable, with fishing mortality either also a decision variable, or capped. Fishers are myopic, making decisions at the beginning of any season to maximize net returns over that season only. Case (a) does not support aggregate rent maximization under open-access conditions, but cases (b) and (c) do.

To keep the analysis simple, aggregate fishing capacity (or number of fishers or boats) over the harvesting season is taken as given and not a function of any rent generated over the season. Some studies of unregulated open-access behaviour (e.g., Androkovich and Stollery, 1991) have

effort per boat set to maximize aggregate seasonal rent for a given number of boats, but also allow free entry and exit of boats so as to drive rent to zero. In the context of the present analysis such an approach is an example of maximisation of within-season rents with respect to effort.

The open-access problem is taken to be best treated as a non-cooperative game, following early sentiments expressed by Wilen (1985, p. 162):

> What I believe is crucial about this approach is the setting of individual decision-making in a gaming structure. This has not been done in other models of fisheries. It is partly a philosophical and partly an empirical issue whether we should model fishermen as parametric decision-makers *à la* standard competitive model or as actively strategic decision-makers who consider rivals' decisions in making their own.

2) Optimal and competitive fishing mortality over period T

Each of n fishers decides to set their rate of fishing mortality at a constant rate over a period of length T so as to maximise their rent over the period, knowing the rate of fishing mortality set by all other fishers. The total uncontrollable fishing mortality that the i-th fisher faces is:

$$g_i = m + \sum_{j \neq i}^{n} f_j \tag{1}$$

where m is the rate of natural mortality, and f_j is the rate of fishing mortality set by the j-th other fishers.

In this section fishing period T is taken as fixed, the same for all fishers, but is treated as a control variable along with f_i in section 6.

By setting fishing mortality at f_i the catch of the i-th fisher is:

$$
\begin{aligned}
h_i &= f_i x_0 \int_0^T \exp((-f_i - g_i)t)dt \\
&= f_i x_0 (1 - \exp(-f_i - g_i)T)/(f_i + g_i)
\end{aligned}
\tag{2}
$$

where x_0 is the start-of-period stock of fish.

The rent accruing to the i-th fisher is:

$$\pi_i = p f_i x_0 (1 - \exp(-f_i - g_i)T)/(f_i + g_i) - c f_i T \tag{3}$$

where p is the price of fish and c is the unit cost of fishing mortality.

The first order condition (FOC) for maximum rent with respect to f_i for the i-th fisher is:

$$\frac{d\pi_i}{df_i} = \frac{px_0}{(f_i + g_i)^2}(\exp((-f_i - g_i)T)(f_iT(f_i + g_i) - g_i) + g_i) - cT = 0 \qquad (4)$$

If for simplicity all fishers are taken to face identical fishing conditions, then by symmetry f_i is the same for all n fishers. Equation (1) becomes:

$$g_i = m + (n-1)f_i \qquad (5)$$

By substituting for g_i from (5) in (4), the f_i for maximum rent is identified as the f_i satisfying:

$$(px_0/(m + nf_i)^2)(\exp((-m - nf_i)T)(nf_i^2T + (mT - n + 1)f_i - m) + m + (n-1)f_i) - cT = 0 \qquad (6)$$

Denoting the f_i satisfying condition (6) as f_i^*, the total harvest for fixed T is:

$$H = x_0nf_i^*(1 - \exp(-m - nf_i^*)T)/(m + nf_i^*) \qquad (7)$$

and rent for the fishery is:

$$\Pi = px_0nf_i^*(1 - \exp(-m - nf_i^*)T)/(m + nf_i^*) - cnf_i^*T \qquad (8)$$

The end-of-period stock is:

$$x_T = x_0\exp((-m - nf_i^*)T) \qquad (9)$$

The first question to be investigated is how optimal f_i varies with n, for $T = 1$. The more complex question of how optimal f_i and T together vary with n is addressed in section 6. Because of the difficulty in obtaining an analytical solution for f_i, a numerical approach is taken.

3) Simulation of competitive fishing mortality for n fishers and $m > 0$

The parameter values used in the numerical simulation are shown in Table 1. The individual fishing mortality f_i was calculated numerically for the FOC of individual single-period maximum rent (condition 6) for values of n from 1 to 100, together with corresponding values of end stock, and industry harvest and rent. The FOC are based on the assumption that a Cournot/Nash Equilibrium attains for each fisher. That is, each fisher knows the fishing mortality set by all competing fishers, treats these settings as beyond their control, and sets their fishing mortality accordingly. Results are shown in Table 2 and Figure 1.

Table 1: Parameter values

Opening stock	x_0	500
Natural rate of mortality	m	0.2
Price of fish	p	1
Per unit cost of fishing mortality	c	50
Length of fishing season	T	1

Table 2: Aggregate competitive fishing mortality by number of fishers for natural mortality = 0.2

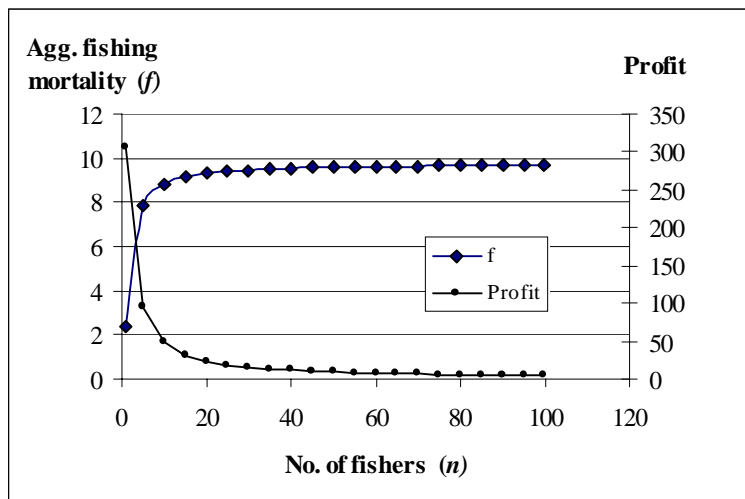| No. of fishers	Aggregate fishing mortality	Aggregate harvest	Aggregate rent	End stock	Length of fishing season
n	$f^* = nf_i^*$	$H = nh_i$	Π	x_1	T
1	2.35	424.98	307.31	38.90	1.00
5	7.85	487.43	94.82	0.16	1.00
10	8.82	488.86	47.75	0.06	1.00
20	9.31	489.45	23.94	0.04	1.00
50	9.60	489.77	9.59	0.03	1.00
100	9.70	489.88	4.80	0.03	1.00

Figure 1: Aggregate competitive fishing mortality by number for natural mortality = 0.2

As n increases from 1 (rent maximisation) to 20, aggregate fishing mortality increases markedly from 2.4 to 9.3, industry rent declines from 307 to 24, and end-of-period stock falls from 39 to 0.04. As n increases from 20 to 100, rent falls to about 5, and end-of-period stock falls to 0.03.

4) Optimal and competitive harvest

In the approach taken by Hannesson and Kennedy (2003), fishers decide harvest level within a period of unspecified length T, for the case where natural mortality is zero. A Schaefer harvest function is used to express catch per unit of time as:

$$y = Ex \tag{10}$$

where E is fishing effort (equivalent to fishing mortality f) and x is stock level.

If the price of fish is p, and the cost per unit of effort is c, then for any stock level x, the cost per unit of fish caught is c/x, and rent per unit of fish caught is $p - c/x$. The rent obtained by fishing stock down from stock x_0 at the beginning of the fishing period to $x_0 - H$ by the end of the fishing period is:

$$\begin{aligned}
\Pi &= \int_{x_0 - H}^{x_0} (p - c/x)dx \\
&= pH - c(\ln(x_0) - \ln(x_0 - H))
\end{aligned} \tag{11}$$

Again suppose there are n fishers. We want to determine H which results in maximum rent, and the competitive harvest h_i of each fisher i that maximises their rent taking the harvests of all other fishers j as given. These are given by the solutions to the problems for $n = 1$ and $n > 1$, respectively. Rent from harvesting h_i is:

$$\pi_i = ph_i - c(\ln x_0 - \ln(x_0 - \sum_{j \neq i}^{n} h_j - h_i)) \tag{12}$$

The FOC for h_i for maximum single-period rent is:

$$\begin{aligned}
\frac{d\pi_i}{dh_i} &= p - c/(x_0 - \sum_{j \neq i}^{n} h_j - h_i) = 0 \\
&\Rightarrow h_i^* = x_0 - \sum_{j \neq i}^{n} h_j - c/p
\end{aligned} \tag{13}$$

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If all fishers face identical fishing conditions, then by symmetry h_i is the same for all n fishers, and equals:

$$h^* = x_0 - (n-1)h - c/p$$
$$= (x_0 - c/p)/n \tag{14}$$
$$\Rightarrow nh^* = H = x_0 - c/p$$

The end-of-period stock is:

$$x_T = x_0 - nh^* = c/p \tag{15}$$

For the sole fisher problem ($n = 1$), h^* is the rent maximising harvest. But total harvest $= nh^*$ is also the rent maximising harvest for $n > 1$. So the fishery is characterised as within-period rent maximising, whether there is just one fisher or many.

The result can be rationalised by arguing that all fishers will continue harvesting until stock is driven down to the level (x_T) at which the return from one more unit of catch (p) equals its cost (c/x_T). No fisher will harvest more.

The result is consistent with much standard analysis. For example, McKelvey (1997, pp. 133-134) refers to what he terms the simplest idealized model of a seasonal fishery. He cites the unit-profit (or marginal-profit) function $\pi(x) = p - c(x)$ where $c(x)$ is the unit cost of harvest inversely related to current within-season stock-level x as typical. He notes that for a break-even stock level S^0 such that marginal profit with respect to stock $= \pi(S^0) = p - c(S^0) = 0$, under competitive conditions, open-access to the fishery stock will be driven down to S^0 by the most rapid approach.

5) Comparing optimal and competitive fishing mortality with optimal harvest for $m = 0$

To compare the fishery equilibrium conditions for different n under the two approaches with identical parameters, the competitive f_i simulation is rerun with $m = 0$. The results are shown in Table 3 and Figure 2. The single-period rent maximising f^* for $n = 1$ results in the same harvest as under the competitive h approach. Setting $m = 0$, $T = 1$ and $n = 1$ in equation (6), the FOC for the competitive f_i approach, gives $x_0 \exp(-f) = c/p$. This states that the end-of-period stock is c/p, which means that the harvest is $x_0 - c/p$, the same as given by equation (14) for the competitive h_i approach. Table 3 shows an end-of-period stock equal to $c/p = 50/1$ for $n = 1$.

Table 3: Aggregate competitive fishing mortality by number of fishers
for natural mortality = 0

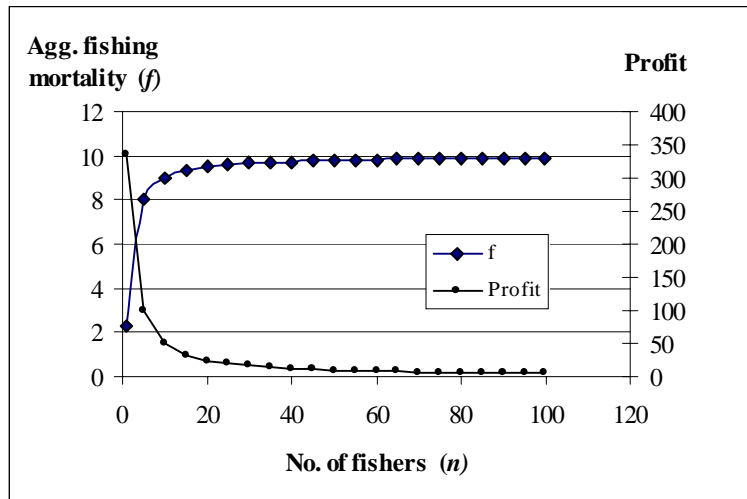| No. of fishers	Aggregate fishing mortality	Aggregate harvest	Aggregate rent	End stock	Length of fishing season
n	$f^* = nf_i^*$	$H = nh_i$	Π	x_1	T
1	2.30	450.00	334.87	50.00	1.00
5	8.00	499.83	99.70	0.17	1.00
10	9.00	499.94	49.94	0.06	1.00
20	9.50	499.96	24.98	0.04	1.00
50	9.80	499.97	9.99	0.03	1.00
100	9.90	499.97	5.00	0.03	1.00

Figure 2: Aggregate competitive fishing mortality and industry
rent by number of fishers for natural mortality = 0

Although the results for both approaches are the same for $n = 1$, they are quite different for $n > 1$. Unlike in the competitive h approach, total harvest climbs with increasing n in the competitive f approach. The question arises as to which approach, modelling fishers as determining competitive f or competitive h, might be deemed more appropriate. Both approaches considered here rely on Cournot-type behaviour for $n > 1$, which is to some extent unrealistic and hence unsatisfactory. Each fisher commits to individually competitive f_i or h_i from the start of the harvesting period, knowing the levels to which all other fishers have committed, levels which they suppose they cannot influence.

An argument against the competitive h_i approach is that no account is taken of the distribution of the harvesting effort of each fisher over the fishing period, or of natural mortality. This means that each fisher would realise that they would gain over other fishers by collecting their catch before other fishers caught theirs. Assuming all fishers are identical means that all fishers would collect their equal shares of the optimal aggregate catch instantaneously at the beginning of the harvesting period. This might be judged unrealistic, perhaps more unrealistic than assuming that fishing effort is applied continuously throughout the fishing period. Koenig (1984) deals with this by placing an upper limit on the rate of harvesting.

The analysis in sections 2 and 3 forces fishing mortality to be applied at a constant rate over a period of specified length. There is no possibility of each fisher taking their total harvest within an instant. Is this an artificial constraint, imposed merely for modeling convenience? Does it preclude fishing stock down just to the level at which within-period rent is maximized? In the next section, the impact on fishery rent as n increases from one is studied when fishers can set the length of the harvesting period as well as fishing mortality.

6) Optimal and competitive fishing mortality and harvesting period T

The analysis of section 2 is extended to make T_i a decision variable of the i-th fisher as well as f_i in maximising individual rent. The resulting impact on aggregate rent is considered first for the sole fisher case ($n = 1$), and then for the competitive fishery case ($n > 1$).

If f_i and m are instantaneous *annual* rates, $T_i > 1$ would imply a harvesting period greater than a year. If the addition to the fish stock occurs annually, the feasible range for the harvesting period is restricted to $0 \leq T_i \leq 1$.

In treating T_i as an individual choice variable, it is assumed that each fisher supposes that for whatever T_i they select, all other fishers will be harvesting for at least as long as T_i. This is justified if each fisher calculates that they would be disadvantaged if they harvest for a longer period than all other fishers because they would face thinner stocks. Accordingly, each fisher assumes their uncontrollable fishing mortality throughout T_i is the rate g_i, defined in equation (1). The FOC for maximum individual rent is:

$$\partial\pi_i / \partial T_i = pf_i x_0 \exp((-f_i - g_i)T_i) - cf_i = 0$$

$$\Rightarrow \quad x_0 \exp((-f_i^* - g_i)T_i^*) = c/p \tag{16}$$

$$\Rightarrow \quad T_i^* = \ln(x_0 p/c)/(f_i^* + g_i)$$

The second derivative is negative, a necessary condition for maximum rent.

Substituting as before in section 2 the RHS of equation (5) for g_i in equation (16) on symmetry grounds gives the optimality condition:

$$T_i^* = \ln(x_0 p/c)/(m + nf_i^*) \tag{17}$$

Optimality conditions (6) and (17) were used for determining the rent maximising solutions in the case of the sole fisher ($n = 1$) with respect to f and T separately, and f and T together. Table 4 shows harvests, rents, and end stocks for the parameter values in Table 1, for positive and zero natural mortality.

Table 4: Rent maximisation ($n = 1$) with f and T as decision variables
for natural mortality = 0.2 and 0.0

Simulation run no.	Natural mortality	Fishing mortality	Length of harvesting season		Harvest	Rent	End stock
	m	f	T	fT	H	Π	x_T
1	0.20	*2.35	**1.00**	2.35	424.98	307.31	38.90
2	0.20	**3.00**	*0.72	2.16	421.88	313.94	50.00
3	0.20	*∞	*0	2.30	450.00	334.87	50.00
4	0.00	*2.30	**1.00**	2.30	450.00	334.87	50.00
5	0.00	**3.00**	*0.77	2.30	450.00	334.87	50.00
6	0.00	*∞	*0	2.30	450.00	334.87	50.00

Key: * denotes rent maximising setting; **Bold figures** denote fixed values.

The following points emerge:

a) When f and T are both decision variables, f^* tends to infinity and T^* tends to zero, for both $m = 0.2$ and $m = 0.0$ (simulations 3 and 6).

b) Harvest, rent and end stock are the same for the cases f^* for fixed T, and T^* for fixed f, for $m = 0$ (simulations 4 and 5), and for both of the f^*, T^* cases (simulations 3 and 6). The product of f and T is the same and equal to 2.30. Rent is maximised.

It can be shown these results hold generally as they can be deduced from the optimality conditions as follows.

a) Substituting the RHS of equation (17) for optimal T in the rent equation (3) and setting the full derivative of rent with respect to fishing mortality equal to zero gives $f^* = \infty$. Equation (17) for $f^* = \infty$ gives $T^* = 0$.

b) For $m = 0$, or if m is insignificant relative to f^*, the optimality condition for f in equation (6) is:

$$\frac{\partial \pi_i}{\partial f} = \frac{px_0}{f^2}\exp(-fT)f^2 T - cT = 0$$

$$\Rightarrow \exp(-f^*T) = c/(px_0) \tag{18}$$

$$\Rightarrow f^* = \ln(px_0/c)/T$$

and the optimality condition for T in equation (17) can be written as:

$$T^* = \ln(px_0/c)/f \tag{19}$$

Thus for the special case of $m = 0$, the optimality conditions are the same for f and T. Equations (18) and (19) together imply:

$$f^*T = fT^* = f^*T^* = \ln(px_0/c) \tag{20}$$

For the parameters used in the simulation runs $\ln(px_0/c) = 2.30$.

Thus in the case of the sole fisher, rent is maximised for all combinations of f and T as decision variables if natural mortality is zero, and for f and T as simultaneous decision variables if natural mortality is positive and finite.

It was shown in sections 3 and 5 that for the competitive fishery ($n > 1$) for particular parameter values, aggregate rent was not maximised for zero or positive natural mortality when fishing mortality was the decision variable and $T = 1$. However it follows from equations (17) and (20) that if T_i is also a decision variable, rent is maximised not only for the sole fisher case, but also the competitive fishery with $n > 1$. The outcome for rent, harvest and end stock is the same as that for the harvest analysis. However, the solution values $f_i^* = \infty$ and $T_i^* = 0$ are unrealistic.

Consider now imposing an upper limit on f_i equal to $\bar{f}_i$, allowing the n fishers to decide T_i only.

The optimality condition for T_i is given by equation (17) with $\bar{f}_i$ replacing f_i^*, or:

$$T_i^* = \ln(x_0 p/c)/(m + n\bar{f}_i)$$

$$\Rightarrow (m + n\bar{f}_i)T_i^* = \ln(x_0 p/c) \tag{21}$$

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If natural mortality $m = 0$, aggregate mortality is $n\bar{f}_i$, and from equation (21) $n\bar{f}_i T_i^* = \ln(x_0 p/c)$, which is the same as condition (20) for optimal aggregate rent. Thus for $n = 1$ equation (21) is the condition for maximum rent for the sole fisher. For $n > 1$, T_i^* is an n-th of T_i^* for $n = 1$, but the aggregate rent is still maximised. The effect of increasing n for the parameters in Table 1 but with $m = 0$ is shown in Table 5 and Figure 3.

Table 5: Competitive harvesting period by number of fishers for individual

ceiling fishing mortality $\bar{f}_i = 2.30$ and natural mortality $= 0$

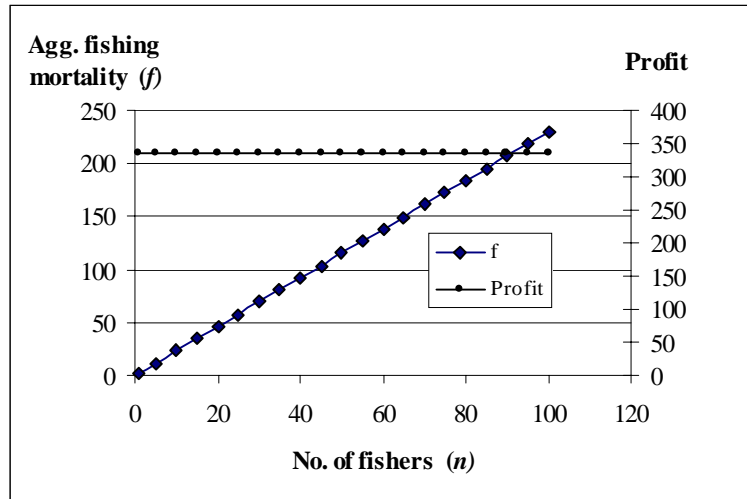| No. of fishers	Aggregate fishing mortality	Aggregate harvest	Aggregate rent	End stock	Length of fishing season
n	$\bar{f} = n\bar{f}_i$	$H = nh_i$	Π	x_T	T_i^*
1	2.30	450.00	334.87	50.00	1.00
5	11.51	450.00	334.87	50.00	0.20
10	23.03	450.00	334.87	50.00	0.10
20	46.05	450.00	334.87	50.00	0.05
50	115.13	450.00	334.87	50.00	0.02
100	230.26	450.00	334.87	50.00	0.01

Figure 3: Competitive harvesting period and industry rent

by number of fishers for $\bar{f}_i = 2.30$ and natural mortality $= 0$

If natural mortality is positive and finite, n fishers fishing at rate $\bar{f}_i$ over harvesting period T_i^* given by equation (21) results in less than maximum possible aggregate rent. However,

perhaps unexpectedly, aggregate rent approaches maximum aggregate rent as n increases. The reason is that as n increases, m becomes smaller relative to $n\bar{f}_i$, and condition (21) approaches condition (20). The effect of increasing n for the parameters in Table 1 with m reset at 0.2 is shown in Table 6.

Table 6: Competitive harvesting period by number of fishers for individual ceiling fishing mortality $\bar{f}_i = 2.30$ and natural mortality $= 0.2$

No. of fishers	Aggregate fishing mortality	Aggregate harvest	Aggregate rent	End stock	Length of fishing season
n	$\bar{f} = n\bar{f}_i$	$H = nh_i$	Π	x_T	T_i^*
1	2.30	414.04	308.11	50.00	0.92
5	11.51	442.32	329.15	50.00	0.20
10	23.03	446.13	331.99	50.00	0.10
20	46.05	448.05	333.42	50.00	0.05
50	115.13	449.22	334.29	50.00	0.02
100	230.26	449.61	334.58	50.00	0.01

7) Conclusion

The issue of whether within-period rent is maximised under open-access conditions is important for the applicability of the result obtained by Weitzman (2002) that fees dominate quotas in regulating fisheries subject to ecological uncertainty. Three ways of casting the fishers' decision problem have been analysed, and the way in which rents and end-of-season stock depends on the number of fishers has been examined.

Results for the open-access ($n > 1$) problem in which fishing mortality is set for a fishing season of fixed length do not support within-season maximisation of aggregate rent. However within-season rent maximisation does result if the fishers' problem is to set the season's harvest, or both fishing mortality and season length, but the results imply instantaneous total catch. Setting a ceiling on individual fishing mortality and making the decision variable the length of the fishing season does result in within-season maximisation of aggregate rent if natural mortality is zero, or otherwise approaches it for a sufficiently large number of fishers.

There are doubtless results to be obtained for other ways of casting the problem, such as making total harvesting costs increase at an increasing rate as fishing mortality increases. There are obviously many criteria to be considered in formulating the problem such as simplicity in expository problems or approximation to reality. However, it has been shown that it is possible to find simple alternative formulations of the fishers' problem which result in within-season aggregate rent maximisation or dissipation.

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