Marine Resource Economics, Volume 21, pp. 251–267
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0738-1360/00 $3.00 + .00

Within-Season Rents: Maximised or Dissipated in an Open-Access Fishery?

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Abstract *It is pervasively argued that the equilibrium outcome for an open-access fishery in which harvesting cost is inversely related to fish stock is inefficient, with complete dissipation of within-season rents. However, some argue instead that within-season rents are maximised. Conditions under which either outcome can be justified are considered. Competitive open-access outcomes are presented for different versions of continuous-time and discrete-time models of within-season fishing. The general conclusion is that in many cases rent maximisation is the more plausible outcome. The issue is important for determining the benefits of different types of regulation under uncertainty, the optimal settings of instruments such as quotas and landing fees, and the way in which open-access outcomes should be modelled in applied work.*

Key words Open-access fishery, within-season rent, non-cooperative game.

JEL Classification Codes D62, Q22.

Introduction

There are two factors often cited as contributing to rent dissipation in unregulated open-access fisheries. One is the stock effect implicit in instantaneous harvest functions, such as the Schaefer function with unitary stock and effort exponents. As stocks are fished down, the cost of catching another fish increases. The other factor is the fishers' inability to claim property rights of the fish, and with them the benefits of foregoing current harvest in return for greater future benefits of harvesting from a stock of greater biomass. Koenig (1984) refers to this as an inter-seasonal stock externality.

One approach to modelling fishers' harvesting over a long or infinite-time horizon is to model harvesting in successive seasons, often of one year, dependent on the immediately preceding stock level. The reason is that recruitment can best be treated as an event at the start of each season, rather than as a continuous process. Fishing and natural mortality and growth in fish weight may be treated as either discrete events or as continuous processes depending on modelling goals.

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The authors thank two anonymous reviewers for their helpful comments on an earlier draft of this paper.

In some dynamic multi-season models, as a simplification, or in the interests of obtaining general results, the within-season harvesting is not explicitly modelled. Instead, an assumption is made on whether, in the absence of regulations, within-season rents are dissipated or maximised. Policy results will depend on which assumption is made.

Cases in point are Weitzman's (2002) stochastic dynamic programming analysis of the superior efficiency of landing fees over quotas as the regulatory instrument if the regulator is uncertain about the stock level when the quotas or fees have to be announced at the start of each season. Weitzman assumes within-season rents are maximised in the absence of regulations for the usual case of unit fishing cost inversely related to stock level. This is key to the result that the imposition of landing fees can be guaranteed to maximise the expected present value of rents across seasons, whereas quotas cannot. Thus, landing fees are the better instrument to overcome inefficiency due to the inter-seasonal stock externality, assuming that no intra-seasonal inefficiency arises from marginal fishing cost rising with falling stock. Hannesson and Kennedy (2005) make the same assumption in extending the analysis to other types of uncertainty using simulation. Another case is the determination of landing fees or quotas in a deterministic setting. Less restrictive fees or quotas would be recommended if within-season rents were assumed to be maximised in the absence of regulations.

The alternative assumption of within-season rent dissipation has been based on diminishing returns to fishing effort (*e.g.*, Gordon 1954; Cheung 1970, Gravelle and Rees 2004), and also on adverse stock effects on the cost per fish caught. An adverse stock effect (or intra-seasonal stock externality) occurs if a fisher, in expending an additional unit of fishing effort, reduces stock. This not only increases their cost per fish caught but the cost per fish caught of all other fishers. An adverse stock effect is implicit in a Schaefer harvest function with a positive stock exponent. It 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; Hartwick and Olewiler 1986; Clark 1990).

If the modelled rent outcome from within-season harvesting is assumed, rather than the product of explicit modelling, a choice has to be made between assuming rent dissipation, rent maximisation, or an outcome in between. In the next section, a heuristic explanation is introduced for within-season rent dissipation (termed 'rational expectations') and another (termed 'adaptive expectations') for within-season rent maximisation. The relative plausibility of the explanations is subsequently considered in the context of alternative continuous-time and discrete-time dynamic models of within-season fishing. Analysis is conducted for four models, differing by decision variables: Model 1 — the optimal constant rate of fishing mortality applied over a fixed harvesting period; Model 2 — the optimal harvest or end-of–period stock; Model 3 — the optimal combination of constant rate of fishing mortality and harvesting period; and Model 4 — a capped rate of fishing mortality applied over the optimal harvesting period. Fishers are treated as myopic, making decisions at the beginning of a season to maximise their net return over that season only. Model 1 does not support aggregate rent maximisation under open-access conditions, whereas Models 2 to 4 do under most circumstances. Model results are derived in subsequent sections and summarised in table 4 in the final section.

The number of fishers or boats, n, over the harvesting season is an indicator of the degree of competition in the fishery. To keep the analysis simple, n is taken as fixed and not a function of rent generated over the season. Numerical results are obtained for n parameterised from 1 to 100. However, if it is assumed that fishers continue to enter the fishery whilst rent is positive, and that there is a fixed cost of entry, then the relevant n in the results tables is given by modelled aggregate rent before charging for the fixed costs, divided by the fixed cost. Some studies of unregulated open-access behaviour (*e.g.*, Androkovich and Stollery 1991) have effort per boat set to maximise 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.

Whilst fixed costs can be accommodated as explained, the basic analysis is conducted without fixed costs and without modelling the determination of n to avoid unnecessary pre-commitment on the following issues:

(*i*) How large are the fixed costs of entry for each fisher? The results should apply for all possible fixed costs, high or low, so nothing is lost by making them zero or close to zero.

(*ii*) Modelling n explicitly as positively related to rent after charging for fixed costs requires a position on whether this is a behavioural assumption, a condition for efficiency, or both.

(*iii*) In dynamic models, the question arises as to whether it is reasonable to assume that n adjusts fast enough to drive rent, after fixed costs, to zero within each season (*e.g.*, Kennedy 1999), or whether there are lags in the adjustment process over seasons (*e.g.*, Bjørndal and Conrad 1987; Brasao, Duarte and Cunha-e-Sa 2000).

These issues are left open. This keeps the focus on the aggregate rent and its efficiency before charging for fixed costs, and away from the aggregate rent after charging for fixed costs, an outcome driven by the assumption of attaining the equilibrium number of fishers within the season. The approach enables Weitzman's (2002) assumptions of all costs being variable and industry within-season rent maximisation under open access, with Homans and Wilen's (1997) assumption of complete dissipation of industry rent, even if all costs are variable.

The open-access problem is 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.

For the analysis here, a fishery is an open-access fishery if it consists of at least two homogeneous competing fishers (*i.e.*, $n > 1$).

Rationale for Rent Dissipation and Rent Maximisation

Rent Dissipation

Let instantaneous harvest, h_i, for the i-th fisher be a positive function of instantaneous fishing effort applied, e_i, and the fish stock, x. Also let fish stock be a negative function of the fishing effort applied by each of the n fishers. Making p the price of fish, and c the cost per unit of fishing effort, instantaneous rent for the i-th fisher can be defined as:

$$\pi_i = ph_i\{e_i, x\{e_1, ..., e_N\}\} - ce_i. \quad (1)$$

The first-order conditions for individual-fisher rent maximisation with respect to fishing effort (ignoring the consequences of the resulting changes in stock from any other decisions to be made) are:

$$\frac{\partial \pi_i}{\partial e_i} = p\left[\frac{\partial h_i}{\partial e_i} + \frac{\partial x}{\partial e_i}\frac{\partial h_i}{\partial x}\right] - c = 0 \quad \forall i. \quad (2)$$

Except in the case of a sole harvester of the stock ($n = 1$), these are not the conditions for the efficient level of individual effort for all fishers which maximises aggregate fishery rent. The efficiency problem is to find optimal settings of all e_i to:

$$\max_{e_i \dots e_n} \sum_{j=1}^{n} \pi_j = \sum_{j=1}^{n} \left(ph_j\{e_j, x\{e_1, ..., e_n\}\} - ce_j\right). \quad (3)$$

The first-order conditions for efficiency are:

$$\frac{\partial \sum \pi_j}{\partial e_i} = p\left[\frac{\partial h_i}{\partial e_i} + \frac{\partial x}{\partial e_i}\sum_{j=1}^{n}\frac{\partial h_j}{\partial x}\right] - c = 0 \quad \forall i. \quad (4)$$

Comparing equation (2) with equation (4), the second term in braces in equation (4) is more negative by:

$$\frac{\partial x}{\partial e_i}\sum_{j=1,\neq i}^{n}\frac{\partial h_j}{\partial x},$$

than that in equation (2). This is the negative external effect on all other fishers of the marginal increment of effort applied by the *i*-th fisher. It follows that for efficient application of effort by the *i*-th fisher, marginal harvest from effort must be larger, and effort lower, than the effort which appears to be optimal applied in isolation.

If $\partial h_j/\partial x = 0$, there is no stock effect, and the optimal individual level of effort coincides with the efficient level: the return in fish from a marginal unit of effort should equal c/p. The presence of the negative stock effect or externality results in the individually optimal effort level being greater than the efficient level, and thus in reduced aggregate rent. Effort by the *i*-th fisher reduces stock, which means that not only must more effort be applied and more cost expended by the *i*-th fisher to catch a fish, but also by all other fishers.

The larger the number of fishers, n, the greater is the external effect and the lower the aggregate rent from the unregulated fishery. Could aggregate rent be completely dissipated if n were large enough? If entry by fishers were costless, this would be the case. If fishers incur a fixed cost on entry, the lower limit to aggregate rent after charging fixed costs would be zero, but rent before charging fixed costs would be positive.

Although this is standard analysis of the inefficiency of an externality, it is not often presented in the fisheries economics literature. It is set in a timeless framework. Cheung (1970, p. 104) refers to the analysis as 'instantaneous and timeless.' The analysis is rarely used to explain how dissipation of rents might occur in practice, perhaps because time matters in practice.

The following heuristic is a candidate explanation. Because there are no explicit dynamics or references to a fishing season, the time period over which effort is applied is unspecified. The explanation could apply to rent depletion occurring instantaneously, within a season, or across seasons. Suppose for simplicity that each additional unit of fishing effort applied is provided by a new entrant at constant unit cost. A potential new entrant considers (irreversible) entry based on an *ex ante* estimate of a positive return for them, given the current level of total effort already committed. The existing effort commitment is clear from counting the number of entrants (vessels) ready to fish. The adverse impact of their entry on the returns of all other committed entrants is ignored. Additional entrants are attracted on this basis. The last entrant is attracted into the fishery anticipating (based on 'rational' calculation) that they will just break even. Then all entrants start fishing over the prescribed period, all are in exactly the same situation, and all discover they are only breaking even on their unit of effort. Fishery rent is zero. It is a moot point whether the cost of each unit that enters is a fixed cost or a variable cost, because entry and unit effort provision costs are combined. This heuristic is described as *sequential individual entry based on* ex ante *rational expectations followed by simultaneous application of committed effort by all entrants*, or 'rational expectations' for short.

Rent Maximisation

A candidate heuristic explanation of how aggregate rent could be maximised within a fishing season, still subject to the negative stock externality, is as follows. There is a given number of fishers ready to fish at the start of the season, say 100. In this account, there is no restriction on the number of units of effort each fisher can apply over the season. They all simultaneously apply one unit of fishing effort at the start of the season and discover that this has been profitable. All 100 boats continue to simultaneously apply additional units, if *ex post* they have found the previous unit to be profitable. They all decide not to apply another unit once they all find the last unit was unprofitable. The outcome is that rent (before any fixed costs are charged) is maximised at a positive level. The fishery has been able to capture rent for each unit of effort expended. This heuristic is described as a process of *stepwise-simultaneous fishing, with an additional unit of effort expended at each step if the rent from the previous unit was positive*, or 'adaptive expectations' for short.

The key to dissipation of aggregate rent under rational expectations is that the *ex ante* unit-rent calculations of each potential entrant are not realised, because they ignore the costs of their entry for all other committed entrants. The key to aggregate rent maximisation under adaptive expectations is that all fishers capture rent as each decision to apply another unit of effort is implemented by all fishers. Adaptive expectations are employed in the sense that the return from the next unit of effort is expected to be the same as that from the previous unit. Due to the stock effect, the return is always lower, but harvesting only continues until all fishers' returns from an additional unit of effort have reached zero.

The obvious question is, which of these heuristic explanations of effort application is more plausible? Neither could be claimed to reflect reality closely, suggesting that a choice might be best made on empirical grounds, based on the nature oe?·he fishery. However, a strong *a priori* case can be made for the adaptive expectations heuristic on the grounds that returns from fishing are uncertain. This may be due to the start-of-season stock being uncertain. Under uncertainty, a feedback rather than an open-loop policy is generally optimal (Jacobs 1967, p. 99), and is therefore more likely to be adopted. Another choice criterion is the consistency of the heuristic explanation with dynamic modelling of the within-season harvesting, assuming a positive correlation between modelling results and reality.

In dynamic modelling of fisheries, fishing mortality, natural mortality, recruitment, and increase in fish weight may be treated either as processes in continuous time or as ordered events occurring at points within time intervals. Because the open-access outcome may depend on which approach is taken, the outcomes for both are investigated with Models 1 to 4 in the following sections. Models 1, 3, and 4 are primarily continuous-time models, with constant rates of fishing and natural mortality over the harvest season. If the per-unit cost of fishing effort is constant, rent per unit of fishing effort declines as stock declines, thus incorporating the equation (2) stock effect. In Model 2, harvest and natural mortality are events. By using the instantaneous Schaefer harvest function (equation (14) below) the stock effect is included. The structure of all four models means that they would be incorporated in an inter-seasonal model by treating recruitment and increase in fish weight as events at the beginning or end of each season.

A case is made for the rational expectations heuristic being more plausible for Model 1, and the adaptive expectations heuristic for Models 2 and 4.

Model 1: Optimal Competitive Fishing Mortality over Fixed Period *T*

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

$$g_i = m + \sum_{j \neq i}^{n} f_j, \tag{5}$$

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

In Model 1 the fishing period, T, is taken as fixed, the same for all fishers. By setting fishing mortality at the constant rate, $f_{i,}$ throughout T, the catch of the i-th fisher is:

$$\begin{aligned} h_i &= f_i \mathrm{x}_0 \int_0^T \exp\big((-f_i - g_i)t\big)dt \\ &= f_i x_0 \big(1 - \exp(-f_i - g_i)T\big)\big/(f_i + g_i)\,, \end{aligned} \tag{6}$$

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

The rent accruing to the i-th fisher is:

$$\pi_i = p f_i x_0 \big(1 - \exp(-f_i - g_i)T\big)\big/(f_i + g_i) - c f_i T\,, \tag{7}$$

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:

$$\frac{d\pi_i}{df_i} = \frac{px_0}{(f_i + g_i)^2}\Big(\exp\big((-f_i - g_i)T\big)\big(f_iT(f_i + g_i) - g_i\big) + g_i\Big) - cT = 0. \tag{8}$$

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 (5) becomes:

$$g_i = m + (n - 1)f_i. \tag{9}$$

By substituting for g_i from equation (9) in (8), the FOC becomes:

$$A\Big(\exp\big((-m - nf_i)T\big)\big(nf_i^2T + (mT - n + 1)f_i - m\big) + m + (n - 1)f_i\Big) - cT = 0. \tag{10}$$

where $A = [px_0/(m + nf_i)^2]$.

Denoting the f_i satisfying condition (10) as f_i^*, the total harvest for fixed T is:

$$H = x_0nf_i^*\big(1 - \exp(-m - nf_i^*)T\big)\big/(m + nf_i^*), \tag{11}$$

and rent for the fishery is:

$$\pi = px_0nf_i^*\big(1 - \exp(-m - nf_i^*)T\big)\big/(m + nf_i^*) - cnf_i^*T\ . \tag{12}$$

The end-of-period stock is:

$$x_T = x_0\ \exp\big((-m - nf_i^*)T\big). \tag{13}$$

The first question to be investigated is how optimal f_i varies with n, for $T = 1$. The more complex Model 3 question of how the optimal combination of f_i and T together vary with n is addressed in a later section.

Simulation of Competitive Fishing Mortality Set by *n* Fishers over One Year, *T* = 1

The same parameter values are used in the numerical simulation of open-access outcomes for all Models 1 to 4. They are shown in table 1.[1] To obtain Model 1 results, because of the difficulty in obtaining an analytical solution for f_i in FOC equation (10), the individual fishing mortality was determined numerically for values of n from 1 to 2,000, together with corresponding values of end stock, industry harvest, and rent. Results are shown for selected n in table 2 and figure 1 for $m = 0$.

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[1] Qualitative model outcomes are not sensitive to the values, although $x_0 > c/p$ is required to ensure that some fishing is optimal and that opening stock is greater than the efficient stock at the end of the season.

Table 1
Parameter Values

Opening stock	x_0	500
Natural rate of mortality	m	0.0, 0.2
Price of fish	p	1
Per unit cost of fishing mortality	c	50
Fixed length of fishing season	T	1

Table 2
Aggregate Competitive Fishing Mortality by
Number of Fishers for Natural Mortality = 0 (Model 1)

No. of Fishers n	Aggregate Fishing Mortality $f^* = nf_i^*$	Aggregate Harvest $H = nh_i$	Aggregate Rent π	End Stock x_1	Length of Fishing Season T
1	2.30	450.00	334.87	50.00	1.00
2	5.12	497.02	240.88	2.98	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
2,000	9.99	499.98	0.25	0.02	1.00

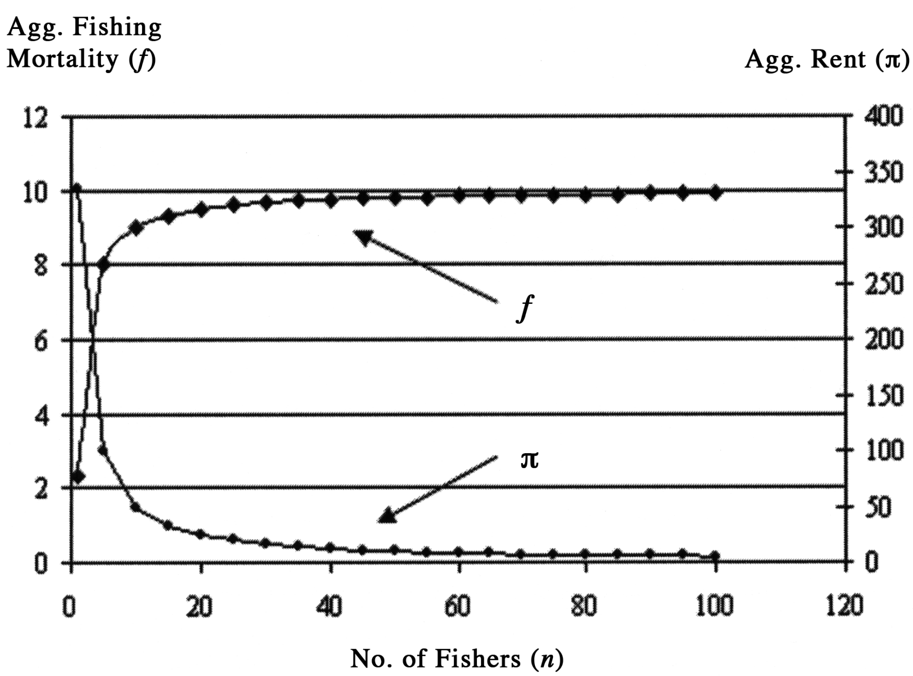

Figure 1. Aggregate Competitive Fishing Mortality and Aggregate Rent By Number of Fishers for Natural Mortality = 0 (Model 1)

The sole fisher result for $n = 1$ is the rent maximising solution, with rent equal to 334.9. The open-access solutions for $n = 2$ to 20 show aggregate fishing mortality increases markedly from 5.1 to 9.5, industry rent declines from 241 to 25, and end-of-period stock falls from 3 to 0.04. As n increases further to 100, rent falls to 5, and end-of-period stock falls to 0.03. This suggests that, under competitive setting of individual rates of fishing mortality over a fixed period, T, depletion of aggregate within-season rent increases as n increases.

However, the plausibility of these solutions as Cournot-Nash equilibria can be questioned. Table 2 shows the end stock for the rent-maximising sole-fisher case to be 50. The instantaneous rent from effort applied to the end stock $(px_T f^* - cf^*)$ should fall to zero, consistent with fishing effort returning positive rent over the time interval $T = 1$. This implies $x_T = c/p = 50$. However, for open-access cases with $n \geq 5$, end stock is less than 0.2. Why would all fishers continue fishing beyond the time interval less than $T = 1$ that stock falls to 50 if they realise each additional unit of effort incurs a loss? If they all did stop once, $x_T = 50$, the aggregate rent would be maximised. This would be the outcome of the adaptive expectations heuristic. It could also be an outcome under the rational expectations heuristic if T, as well as f, were treated as decision variables. It all depends on how reasonable it is to treat T as fixed on grounds of either observed behaviour or an approximation for modelling convenience.

A similar problem arises in the sole-fisher case facing uncontrollable mortality, not from competitors, but from positive natural mortality.[2] Rent is lower than the maximum rent for $m = 0$. The maximum rent for $m = 0.2$ and $T = \bar{T} = 1$ is 307.3 with $f^* = 2.35$. The highest rent for fixed $\bar{f} = 2.35$ is achieved at 308.6 for $T^* = 0.90$. The f^* for any positive $\bar{T}$ gives a rent which always can be increased by reducing $\bar{T}$. To achieve the maximum rent of 334.9 for the case where $m = 0.2$ necessitates T approaching zero and f approaching infinity. Of course this is not a practical outcome. It results from the assumption that the unit cost of effort is constant whatever the effort level. The impact on aggregate open-access rent when T is a decision variable is considered later with Models 3 and 4.

Homans and Wilen (1997, Appendix A) point out in modelling open-access behaviour with constant variable costs that the fishing industry may recognise a maximum season length, $T_{\max}$, beyond which additional application of effort would attract losses, "The industry would always choose not to incur such losses by truncating fishing at $T_{\max}$." They, however, accept that capacity enters in each season until within-season rents are fully dissipated, which applies even if fixed capital costs are zero.

Model 2: Optimal Simultaneous Harvesting

Consider a discrete-time, within-season model with a Schaefer harvest function used to express instantaneous catch as:

$$y = Ex, \tag{14}$$

[2] If growth in individual fish weight were modelled as a continuous–time process over the season, the net effect of natural mortality and weight increase could be a positive growth rate. In this case, marginal rent with respect to time would be positive rather than negative at the end of the season of length $T = 1$. However, as n increases beyond 1, any positive growth rate facing the i-th fisher due to weight increase is more than offset by the increased fishing mortality induced by the other fishers.

where E is instantaneous 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 season to $x_0 - H$ by the end of the fishing season is:

$$\Pi = \int_{x_0-H}^{x_0} (p - c/x)dx \tag{15}$$

$$= pH - c\big(\ln(x_0) - \ln(x_0 - H)\big).$$

Again, suppose there are n fishers. Let h_i be the harvest of the i-th fisher that maximises their rent, taking as given the harvests of any other fishers, indexed by $j \neq i$. Rent from harvesting h_i is:

$$\pi_i = ph_i - c\left(\ln x_0 - \ln\left(x_0 - \sum_{j\neq i}^{n} h_j - h_i\right)\right), \tag{16}$$

where $\sum_{j\neq i}^{n} h_j = 0$ for $n = 1$. The FOC for h_i for maximum within-season rent is:

$$\frac{d\pi_i}{dh_i} = p - c\bigg/\left(x_0 - \sum_{j\neq i}^{n} h_j - h_i\right) = 0 \tag{17}$$

$$\Rightarrow h_i^* = x_0 - \sum_{j\neq i}^{n} h_j - c/p\,.$$

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

$$h^* = x_0 - (n-1)h - c/p \tag{18}$$

$$= (x_0 - c/p)/n$$

$$\Rightarrow nh^* = H = x_0 - c/p\,.$$

The end-of-period stock is:

$$x_T = x_0 - nh^* = c/p\,. \tag{19}$$

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

Natural mortality can be treated as a loss of fish stock, x_m, an event occurring either before or after the fishing period, without altering the rent-maximising conditions.

The result is consistent with other discrete-time analyses. For example, McKelvey (1997, pp. 133–4) refers to what he terms the simplest idealised 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 marginal break-even stock level, S^0, such that marginal profit with respect to stock equals $\pi(S^0) = p - c(S^0) = 0$, under competitive conditions, open access to the fishery stock will be driven down to S^0 by the most rapid approach.

Comparing Model 1 and Model 2 Outcomes for m = 0

There is one Model 1 case which gives the same outcome as Model 2. This is the case of the sole fisher ($n = 1$) harvesting over any predetermined period, T, facing zero natural fish-mortality ($m = 0$). Rent, catch, and end stock for any start stock are the same for both models. In equation (10), the FOC for the competitive f_i approach gives $x_0 \exp(-fT) = c/p$. 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 (18) for the competitive h_i approach. Table 2 shows the Model 1 end-of-period stock is $c/p = 50/1$ for $n = 1$.

Although Model 1 and 2 results are the same for $n = 1$ and $m = 0$, they are quite different for open access ($n > 1$). For Model 2, aggregate rent is still maximised, whereas for Model 1 total harvest climbs and aggregate rent falls with increasing n. The adaptive expectations heuristic is a plausible expository description of the process underlying the Model 2 outcome. It is not plausible for describing the process for the Model 1 outcome, because Model 1 does not incorporate an optimal stopping rule. The rational expectations heuristic may be applicable to Model 1, but only to a limited extent. It describes a process of individual fishers committing to fishing effort which will maximise their returns, but under the artificial constraint of a mandated predetermined length of fishing season.

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.

Model 3: Optimal Competitive Fishing Mortality and Harvesting Period *T*

In treating T_i as an individual choice variable, each fisher supposes that 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 harvested 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 at the rate g_i, defined in equation (5). Substituting T_i for T in rent equation (7), and partially differentiating with respect to T_i, gives the FOC for optimal T_i :

$$\begin{aligned} \partial\pi_i/\partial T_i &= pf_i x_0 \exp\big((-f_i - g_i)T_i\big) - cf_i = 0 \qquad (20)\\ \Rightarrow \quad & x_0 \exp\big((-f_i - g_i)T_i^*\big) = c/p \\ \Rightarrow \quad & T_i^* = \ln(x_0\, p/c)/(f_i + g_i)\,. \end{aligned}$$

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

Substituting the right-hand side (RHS) of equation (9) for g_i in equation (20) (on symmetry grounds, as before) gives the optimality conditions:

$$T_i^* = \ln(x_0 p/c)/(m + nf_i), \tag{21}$$

and by the Envelope theorem:

$$T_i^* = \ln(x_0 p/c)/(m + nf_i^*). \tag{22}$$

Considering the solution for the cases where $n > 1$ and $m > 0$, substituting the RHS of equation (21) for optimal T in the rent equation (10) and setting the full derivative of rent with respect to fishing mortality equal to zero gives $nf_i^* = \infty$. Equation (21) for $nf_i^* = \infty$ gives $T_i^* = 0$.

The individual fisher is caught up in a race to harvest. For a constant rate of effort application, any delay means an uncontrollable reduction in stock from fixed rates of natural fish mortality and/or fishing mortality from the effort of competing fishers, and a consequent increase in the cost of catching an additional fish. If the cost of a unit of effort does not increase with the rate of effort applied, it is optimal to extract the total harvest instantaneously at the start of the season.

The forces behind this outcome can also be seen in figure 2 for the case of n = 10 and $m = 0$. Two schedules are shown in $f - T$ space, 'nf_i^* for given T_i' (determined numerically), and 'T_i^* for given nf_i' (equation [21]). Suppose nf_i^* is determined for T_i = 1. The nf_i^* is only a Nash equilibrium if the season length $T_i = 1$ is mandated. The 'T_i^* for given nf_i' schedule shows that if T_i can be chosen, it is optimal to stop fishing earlier and thereby avoid accumulating losses. The nf_i^* recomputed for T_i^* will be higher. Again a new, lower T_i^* will be found. The eventual outcome is $nf_i^* \to \infty$, $T_i^* \to 0$ and from equation (21), $T^* nf_i^* = \ln(x_0 p/c)$. Any finite m can be treated as equal to zero. The outcome appears in figure 2 as the north-west point towards which the two schedules approach intersection.

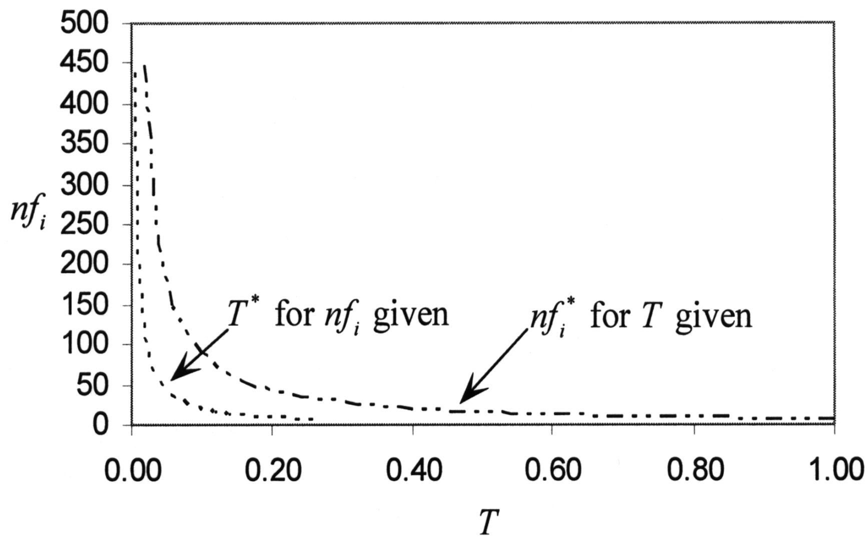

Figure 2. Optimal Aggregate Fishing Mortality for T Given, and Optimal T for Aggregate Fishing Mortality Given, for $n = 10$ and $m = 0$

For the sole fisher case (n = 1) and m = 0, there is no rush to harvest. In this case the two schedules in figure 2 coincide, plotting f^* for any T, and T^* for any f. This can be argued as follows. The optimality condition for f in equation (10) is:

$$\frac{\partial \pi_i}{\partial f} = \frac{px_0}{f^2}\exp(-fT)f^2T - cT = 0 \tag{23}$$
$$\Rightarrow \exp(-f^*T) = c/(px_0)$$
$$\Rightarrow f^* = \ln(px_0/c)/T \,,$$

and the optimality condition for T in equation (21) is:

$$T^* = \ln(x_0 p/c)/f \,. \tag{24}$$

Both conditions map out the same rectangular hyperbola. For the parameters used in the simulation runs, $\ln(px_0/c)$ is equal to 2.30. Thus, the Model 1 solution for T = 1 shown in table 2 is readily determined as f^* = 2.30, with end-of-season stock $x_T = c/p = 50$, and rent $\pi = px_0 - c[1 + \ln(x_0\, p/c)] = 335$. Writing Π as aggregate rent, a function of optimal aggregate fishing mortality, the relationship between the aggregate rents associated with the schedules 'nf_i^* for given T_i' (π) and 'T_i^* for given nf_i' (Π^{-1}) in figure 2 is summarised by:

$$\Pi^{-1}\left\{T^*\left\{nf_i^*\{T'\}\right\}\right\}\begin{cases} = \Pi\{nf_i^*\{T'\}\} \ \ \forall T' & \text{for } m = 0 \text{ and } n = 1 \\ > \Pi\{nf_i^*\{T'\}\} \ \ \forall T' > 0 & \text{otherwise.}\end{cases} \tag{25}$$

In all other cases where there is a rush to fish, (n > 1 and/or m > 0), the solution $nf_i^* = \infty$, $T_i^* = 0$ must also satisfy equation (22). This imposes the same conditions on aggregate fishing mortality and season length as for the sole fisher, zero natural mortality case, so the same maximum rent, harvest, and end stock values apply.

Thus, rent is maximised not only for the sole-fisher case, but also the competitive fishery with $n > 1$. A practical problem is that the solution values $nf_i^* \to \infty$ and $T_i^* \to 0$ are unrealistic. Assuming that the unit effort cost, c, would be unchanged as $f_i^* \to \infty$ is clearly untenable. One solution would be to assume effort cost functions with unit effort cost rising with effort, of which there are many. Another solution is to retain season length as a decision variable, but to cap the rate of fishing mortality (see Koenig 1984). This is considered in the next section.

Model 4: Optimal Harvesting Period *T* with Fishing Effort Capped

In Model 4 an upper limit is imposed on f_i equal to $\bar{f}_i$, reflecting the maximum capacity of each fisher, allowing the n fishers to decide T_i only. The optimality condition for T_i is given by equation (21) after substituting $\bar{f}_i$ for f_i:

$$T_i^* = \ln(x_0 p \,/\, c)/(m + n\bar{f}_i)\,. \tag{26}$$

If natural mortality $m = 0$, aggregate mortality is $n\bar{f}_i$, and condition (26) is the same as condition (24) for optimal aggregate rent for the sole fisher. For $n > 1$, T_i^* is an n-th of

T_i^* for $n = 1$, but the aggregate rent still equals that of the sole fisher.

If natural mortality is positive and finite, n fishers fishing at rate $\bar{f}_i$ over harvesting period T_i^* given by equation (26) results in less than maximum possible aggregate rent. However, 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 (26) approaches condition (24). The effect of increasing n for the parameters in table 1 with $m = 0.2$ is shown in table 3.

Aggregate rent for $n = 1$ is 308.11. Once n reaches 10, aggregate rent is within 1% of the maximum rent of 334.87 for the sole fisher case with $m = 0$, shown in the first row of table 2. Optimal end-stock = 50 is reached for all n.

Discussion and Conclusion

The issue of whether within-season 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 if regulators must set the fees or quotas before uncertainty about the start-of-season stock has been resolved. He sees the result as significant enough to "warrant a serious reconsideration of the entire set of issues in fisheries economics" (p. 328). However, the result relies on an assumption of industry maximisation of within-season rent. He incorporates what he terms the 'free-access zero-profit condition' (p. 333), but is more accurately a zero marginal profit condition, and hence a condition for profit maximisation. Use of the condition is not questioned.

The issue is important in determining the efficient setting of fees, quotas, and other regulatory instruments in a deterministic framework. Tighter regulations will be required if open-access rents are dissipated. It also affects the outcome of modelling dynamic competitive harvesting, with or without a competitive open-access fringe.

At least three approaches can be taken to resolve the issue: (*i*) investigate the outcome when open-access fishers are modelled as private, within-season rent maximisers, taking the decisions of the rest of the industry as beyond their control for a range of commonly used fisher decisions; (*ii*) consider the plausibility of

Table 3
Competitive Harvesting Period, T_i, by Number of Fishers for Individual Ceiling Fishing Mortality $\bar{f}_i = 2.30$ and Natural Mortality = 0.2 (Model 3)

No. of Fishers n	Aggregate Fishing Mortality $\bar{f} = n\bar{f}_i$	Aggregate Harvest $H = nh_i$	Aggregate Rent π	End Stock x_T	Length of Fishing Season T_i
1	2.30	414.00	308.11	50.00	0.9210
2	4.60	431.25	320.92	50.00	0.4797
5	11.50	442.31	329.15	50.00	0.1968
10	23.00	446.12	331.99	50.00	0.0992
20	46.00	448.05	333.42	50.00	0.0498
50	115.00	449.22	334.29	50.00	0.0200
100	230.00	449.61	334.58	50.00	0.0100
2,000	4,600.00	449.98	334.86	50.00	0.0005

behavioural and information assumptions underlying rent dissipation and rent maximisation; and (*iii*) empirically evaluate which hypothesis better matches real-world behaviour. The first two have been considered above.

Results of the first approach applied to the four models are summarised in table 4, with reference to supporting equations and tables. All four models incorporate a stock effect for the multi-fisher case, which results in the cost of harvesting an additional fish increasing for all fishers following a fall in stock. For all models, the same maximum rent, π^*, is obtained for the case of the sole-owner facing zero natural mortality. However, different results are obtained for competitive fishers ($n > 1$) facing natural mortality $m \geq 0$. Only Model 1 (f^*, $T = 1$) has rent dissipation as an outcome, with dissipation a positive function of n. However, the assumption of fixed

Table 4
Summary of Within-Season Rent Outcomes by Model,
Natural Mortality (m), and Number of Fishers (n)

		Model Decision Variables and Constraints			
		Model 1	Model 2	Model 3	Model 4
Parameters		f Subject to $T = 1$	h	f,T $(m + nf_i^*)T^*$ $= \ln(px_0/c)$	T Subject to $f = \bar{f}$
Rate of Natural Mortality	No. of Fishers				
$m = 0$	$n = 1$	$\pi = \pi^*$ Eq. 23, Table 2	$\pi = \pi^*$ Eq. 18	$\pi = \pi^*$ Eqs. 23, 24	$\pi = \pi^*$ Eq. 26
	$n > 1$	$\pi < \pi^*$ $\pi \to 0$ as $n \to \infty$ Eq.10, Table 2	$\pi = \pi^*$ Eq. 18	$\pi = \pi^*$ Eq. 22	$\pi = \pi^*$ Eq. 26
$m > 0$	$n = 1$	$\pi < \pi^*$ Eq. 10	$\pi = \pi^*$ Eq. 18	$\pi = \pi^*$ Eq. 22	$\pi < \pi^*$ Eq. 26, Table 3
	$n > 1$	$\pi < \pi^*$ $\pi \to 0$ as $n \to \infty$ Eq. 10	$\pi = \pi^*$ Eq. 18	$\pi = \pi^*$ Eq. 22	$\pi < \pi^*$ $\pi \to \pi^*$ as $n \to \infty$ Eq. 26, Table 3

Key: Eq. for equation reference to FOC.

Notes:

π^* is the maximum aggregate rent across all models for natural mortality $m = 0$.

For Model 2:
Results for $m > 0$ assume natural mortality is an event, either before or after fishing.

For Model 3:
In the case of $m > 0$ and $n > 1$, $nf_i^* \to \infty$, $T_i^* \to 0$ must hold.
In the case of $m = 0$ and $n = 1$, the only requirement is:

$$nf_i^*, T_i^* > 0, \text{ and } nf_i^* T_i^* = \ln(x_0 \; p/c) \text{ (Eqs. 23, 24).}$$

In the case of $n = 1$, and $m > 0$ is insignificant compared to nf_i^*, and can therefore be treated as $m = 0$ in Eq. 21.

T may be considered unsatisfactory for $n > 1$ and $m > 0$, because for these cases for any constant f applied over fixed T, a higher rent can always be obtained over a lower T. It seems unreasonable to assume fishers would be bound by a minimum fishing period.

Model 3 (f^*, T^*) has rent maximisation as the outcome for all n and m. However, except in the case of $n = 1$ and $m = 0$, the solutions are unique with $f_i^* \rightarrow \infty$ and $T_i^* \rightarrow 0$. These solutions may appear unreasonable on the grounds that the per unit cost of fishing effort would no longer remain constant as fishing effort increased sharply. On the other hand, Homans and Wilen (1997, p. 17) refer to many fisheries in which the fishing season has been reduced to "a few weeks, days or even hours." Model 2 (h^*) can accommodate $\pi = \pi^*$ for all m and n, and Model 4 (T^*, $\bar{f}$) also for all n for $m = 0$ and for $m > 0$ for large n. Thus many game-theoretic models favour a rent maximisation outcome.

The second approach tests the plausibility of explanations of rent dissipation and rent maximisation when fishing is subject to a stock externality. A plausible case can be presented for a congestion externality leading to usage of a facility, such as a highway, to the point that marginal private net benefit is zero, and hence average and total social net benefit are zero. Whilst marginal private net benefit is positive, more users are attracted to the facility, and marginal private net benefit continues to decline. What makes this plausible is the absence of any adverse carryover from the stage of previous facility use. However, in the fishery, the private net returns from entry at any point in the season depend not only on the number fishing at that time, but on the number fishing at all previous stages from the start of the season. The adverse effect of the stock externality is cumulative through time in a way that the congestion externality is not. This forces a contrived two-stage scenario in the rational expectations heuristic for explaining rent dissipation. In the first stage, decisions are made on entry, but no fishing occurs. In the next stage, all entrants start fishing simultaneously and earn zero rent. If any entrants could start fishing before others entered, the initial entrants would have captured some of the season's rent.

The adaptive expectations heuristic underlying rent maximisation is more persuasive. All fishers are making step-by-step effort decisions based on their marginal net return information, rather than on estimated total net returns (which must take account of what decisions all other fishers will make) before the start of fishing. Stopping fishing when marginal net return reaches zero ensures rent is maximised. This is the basis of the rent maximisation outcomes of Models 2 and 4. The explanation is plausible in a deterministic framework, and also in a stochastic framework where stocks and returns are uncertain. A feedback policy is likely to dominate an *ex ante* open-loop policy.

Economics gains much mileage from *a priori* reasoning, but when, as in this instance, reasoning can lead to quite different predicted outcomes, there is a strong case for taking up the third approach of empirical testing of the two hypotheses. However, suppose relevant empirical information on open-access behaviour is lacking for a study of the merits of alternative regulations. It may be desirable to conduct simple analysis under both hypotheses and report the difference in results. But a good case can be made for placing more weight on the results from assuming within-season rent maximisation.

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