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Economic instruments for achieving ecosystem objectives in fisheries management

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An aggregative model of fisheries is developed in the context of the ecosystem. Rules for optimal harvesting are derived and their content is examined. An important result with obvious practical implications is that it may be optimal to pursue unprofitable fisheries in order to enhance the overall economic contribution from the ecosystem. Another interesting result is that modifications of single-species harvesting rules may be required even when there are no biological interactions between the species. The possibility of multiple equilibria and complicated dynamics and their implications for sustainability are briefly discussed. Equations for the valuation of ecosystem services are derived. Only two classes of economic instruments capable of optimal management of ecosystem fisheries have been identified so far, namely (a) corrective taxes and subsidies (Pigovian taxes) and (b) appropriately defined property rights. Of these, Pigovian taxes are informationally demanding perhaps to the point of not being feasible. In contrast, property-rights-based regimes are informationally much more efficient and therefore appear to constitute a more promising overall approach to the management of ecosystem fisheries. The employment of the latter for the management of ecosystem fisheries is discussed and some of the implications are explored.

Key words: ecosystem fisheries, ecosystem fisheries management, fisheries management, individual transferable quotas, multispecies fisheries, multispecies fisheries management.

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Introduction

This paper is concerned with the management of multispecies fisheries within the context of the ecosystem, or, in short, ecosystem fisheries. The approach adopted is an economic one, i.e. the management objective is to maximize the economic yield of the fishing activity.

Development of the economic theory of multispecies fisheries has proceeded mostly in terms of a few, usually two or three, species (May *et al.*, 1979; Pauly, 1982; Hannesson, 1983; Clark, 1985; Flaaten, 1988, 1991). Clearly, this approach, although capable of providing valuable insights, is not well suited to the study of complete ecosystem fisheries. In carrying out the analysis within the framework of a general ecosystem fisheries model (Arnason, 1998), I attempt to provide a more comprehensive view of the pertinent aspects of ecosystem fisheries and their management.

The paper is divided into two main sections. In the first, I develop a general aggregative ecosystem fisheries model and analyse its properties. In the second section, I examine various methods for managing ecosystem fisheries, in particular property rights-based methods.

A general ecosystem fisheries model

This section deals with the modelling and analysis of ecosystem fisheries. In order to focus on the key structural elements of the problem, the modelling is restricted to aggregative, non-stochastic representations. I first model the ecosystem then the fishing activity and, having combined the two, I examine the features of optimum harvesting paths.

Ecosystem description

Consider an ecosystem containing I species. Let the biomass of these species be represented by the $(1 \times I)$ vector $\mathbf{x}$, and let the biomass growth for the species be described by the functions

$$\dot{x}_i = G^i(\mathbf{x},\mathbf{z}),\ i=1,2,\ldots I$$

where the vector $\mathbf{z}$ represents habitat variables. The corresponding $(1 \times I)$ vector of biomass growth functions for all I species is:

$$\dot{x} = \mathbf{G}(\mathbf{x},\mathbf{z}) = (G^1(\mathbf{x},\mathbf{z}),\ G^2(\mathbf{x},\mathbf{z}),\ \ldots,\ G^I(\mathbf{x},\mathbf{z})) \qquad (1)$$

I impose several restrictions on the biomass functions. First, habitat is regarded as exogenous and, consequently, explicit reference to these variables is dropped. Second, I assume that, for each species included in the ecosystem, a particular (non-negative) vector **x** exists such that biomass growth is strictly positive. If this wasn't the case, the species obviously could not survive and therefore could be dropped from the analysis. Third, for analytical convenience I assume that the biomass functions are twice continuously differentiable and concave. Finally, I assume that the growth function of each species exhibits the usual domed-shape with respect to its own biomass.

The representation in (1), even with the above restrictions imposed, is fairly general. All species present in the ecosystem potentially influence the biomass growth of all species. The species interactions are captured by the Jacobian matrix

$$\mathbf{G_x}(\mathbf{x}) = \begin{pmatrix} G^1_{x1} & \cdot & \cdot & G^1_{x1} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ G^1_{x1} & \cdot & \cdot & G^1_{x1} \end{pmatrix},$$

which is often referred to as the community matrix.

This ecosystem representation obviously includes the usual single-species model as a special case ($I=1$). To be concrete, we then have the biomass growth function:

$$\dot{x} = G(x),$$

and the Jacobian (community) matrix is reduced to the scalar $G_x(x)$.

Fisheries description

For convenience of presentation, I shall assume that each species in the ecosystem can be targeted for fishing. This is totally unrestrictive because, as we will see, any level of by-catch is permitted. Thus, an inability to target a species can be taken care of by the appropriate by-catch specification. Let the $(1 \times I)$ vector **e** represent aggregate fishing effort for each species. Each element of this vector e_i represents fishing effort directed to a species i. The corresponding harvest is given by the generalized harvesting function:

$$y_i = Y^i(\mathbf{e},\mathbf{x}), \tag{2}$$

where y_i is the harvest of species i. This harvesting function is fairly general. First, all biomasses influence the harvest of species i, not just the biomass of the species itself. It is not difficult to imagine situations where cross-species harvesting effects of this nature might take place. For instance, the catchability of one species may be influenced by the presence of another species. Tunas and dolphins, and capelin and humpback whales are cases in point. The magnitude of this effect in specific cases is an empirical problem. Second, the catch of species i depends on the fishing effort for all species in the ecosystem. Thus, equation (2) allows for by-catch in a natural way. For instance, $Y^i_{ej}(\mathbf{e},\mathbf{x}) \equiv \partial Y^i/\partial e_j$ represents the marginal by-catch of species i in response to an increased fishing effort on species j.

A harvesting function like (2) is assumed to apply to each species. For mathematical convenience, we generally take these harvesting functions to be twice continuously differentiable, increasing in own fishing effort and biomass and concave. Moreover, since some fishing effort is needed to generate harvest and some biomass of species i to generate harvest of species i, we have:

$$Y^i(\mathbf{0},\mathbf{x}) = Y^i(\mathbf{e},\mathbf{0}) = Y^i(\mathbf{e}, x_1, x_2, \ldots, x_{i-1}, 0, x_{i+1}, \ldots, x_I) = 0.$$

The whole fishery can be represented by the vector of harvesting functions

$$\mathbf{y} = \mathbf{Y}(\mathbf{e},\mathbf{x}). \tag{3}$$

The costs function corresponding to the harvesting activity for each species may be written as

$$c_i = C^i(\mathbf{e},\mathbf{w}),\ i = 1,2,\ldots I, \tag{4}$$

where the vector w represents the vector of input prices. Because these are regarded as exogenous in this analysis, explicit reference to them will be dropped from the notation.

Note that (4) is a fairly general representation of the fisheries cost function in the ecosystem context. In particular, the derivative $C^i_{ej}(e)$ represents the marginal cost in fishery i of increased fishing effort in fishery j. In economic jargon, such an effect is referred to as a production externality. While it is easy to think of situations where an effect of this kind might be important – for instance, crowding on the fishing grounds or in landing ports – its empirical relevance clearly depends on the particular situation.

We assume that the cost functions are increasing when fishing effort increases, and, for mathematical convenience, are convex. Total fishing costs can be represented by the $(1 \times I)$ vector

$$\mathbf{c} = \mathbf{C}(\mathbf{e},\mathbf{w}). \tag{5}$$

Our description of the harvesting activity is summarized in equations (3) and (5). Obviously, the vector of fishing effort on individual species (e) plays a central role. Note that, in the extreme case, where no targeting is possible, the fishing effort vector may be expressed as a vector of constants (fixed relative fishing efforts) multiplied by a scalar (the intensity of fishing effort). More formally:

$$\mathbf{e}=\alpha \cdot \mathbf{e}_0,$$

where $\mathbf{e}_0$ is the vector of relative fishing efforts and a is a measure of the intensity of fishing effort. It immediately follows that all species in the ecosystem have to be fished indiscriminately according to their respective harvesting functions, $y_i=Y^i(\alpha \cdot \mathbf{e}_0,x)$ for all i. Therefore, ecosystem management, in the sense of adjusting fishing effort on species is simply not possible and the whole ecosystem has to be exploited as if it consisted of only one species. Thus, the assumption that it is possible to target individual species, or at least subsets of species, separately is fundamental to the practical relevance of ecosystem analysis.

Profits and rents

Combining the economic and biological part of the model, the evolution of species biomasses is defined by the following vector function:

$$\dot{x}=\mathbf{G}(\mathbf{x})-\mathbf{Y}(\mathbf{e},\mathbf{x}). \tag{6}$$

This representation implicitly assumes that fishing activity only influences biomass growth via its extraction of biomass in the form of harvests.

Profits, or fisheries rents, in fishery i are

$$\pi^i=Y^i(\mathbf{e},\mathbf{x})-C^i(\mathbf{e}),$$

where for convenience of notation the unit price of harvest has been normalized to be equal to unity. This is, of course, equivalent to redefining the units in which the volume of harvest is measured and, consequently, that of biomass as well, so as to make the price equal unity.

Fisheries rents in all fisheries are contained in the $(I \times 1)$ vector

$$\pi=\mathbf{Y}(\mathbf{e},\mathbf{x})-\mathbf{C}(\mathbf{e}).$$

Total fisheries rents, or profits from the ecosystem as a whole, may be written as:

$$\pi=\Sigma_i\pi^i\equiv\Sigma_i Y^i(\mathbf{e},\mathbf{x})-C^i(\mathbf{e})\equiv\mathbf{1}\cdot(\mathbf{Y}(\mathbf{e},\mathbf{x})-\mathbf{C}(\mathbf{e}))\equiv\mathbf{1}\cdot\pi,$$

where π represents total profits at time t and **1** represents a $(1 \times I)$ vector of ones. Finally, the present value of fisheries rents is:

$$V=\int_0^\infty \pi\cdot\exp(-rt)dt=\int_0^\infty \mathbf{1}\cdot(\mathbf{Y}(\mathbf{e},\mathbf{x})-\mathbf{C}(\mathbf{e}))\cdot\exp(-rt)dt,$$

where t represents time and r>0 is the rate of discount (interest). Thus, $\exp(-rt)\equiv\mathbf{e}^{-rt}$ is the discount factor appropriate to profits at time t.

Optimum ecosystem fisheries

I first examine the case where the social objective is to maximize the present value of economic rents from the fisheries. This, of course, is the usual approach in analytical fisheries economics. The maximization problem is to find the time path for the fishing effort vector that maximizes the present value of profits from the fishery. More formally, I seek to:

$$\text{Maximize } V=\int_0^\infty \pi\cdot\exp(-rt)dt =\int_0^\infty \mathbf{1}\cdot\pi\cdot\exp(-rt)dt \tag{7}$$

$\{\mathbf{e}\}$

Such that $\dot{x}=\mathbf{G}(\mathbf{x})-\mathbf{Y}(\mathbf{e},\mathbf{x})$,
$\pi=\mathbf{Y}(\mathbf{e},\mathbf{x})-\mathbf{C}(\mathbf{e})$,
$x\geq 0$,
$e\geq 0$.

A Hamilton function corresponding to this problem may be written as:

$$H=\mathbf{1}\cdot\Pi(\mathbf{e},\mathbf{x})+\lambda\cdot(\mathbf{G}(\mathbf{x})-\mathbf{Y}(\mathbf{e},\mathbf{x})),$$

where the $(I \times 1)$ vector $\pi\Pi(e,x)$ represents profits, i.e. $\Pi(e,x)\equiv Y(e,x)-C(e)$. The vector λ plays a crucial role in the subsequent analysis. Along the optimum path, the elements of λ (λ_1, λ_2, ... λ_I,) represent the shadow values of the respective biomasses (x_1, x_2, ... x_I,). In other words, λ provides a measure of the economic contribution of the various species biomasses in terms of the objective function.

Necessary conditions for solving (7) include (Pontryagin *et al.*, 1962):

$$\mathbf{1}\cdot\Pi\varepsilon\lambda\cdot\mathbf{Y}_e=0, \tag{7.1}$$

$$\dot{\lambda}-r\cdot\lambda=-\mathbf{1}\cdot\mathbf{Y}_x-\lambda\cdot(\mathbf{G}_x-\mathbf{Y}_x), \tag{7.2}$$

$$\dot{x}=\mathbf{G}(\mathbf{x})-\mathbf{Y}(\mathbf{e},\mathbf{x}). \tag{7.3}$$

Equations (7.1) to (7.3) provide 3I conditions that along with the appropriate initial and transversality conditions are in principle sufficient to determine the optimum time paths of the 3I unknown variables, namely the $(1 \times I)$ vectors λ, **e** and **x**. The first two are in many respects central to the solution. Equation (7.1) gives the rule for the optimum behaviour of the fishing industry at each point in time. According to this rule, fishing effort in each fishery should be expanded until the overall marginal profits equal the marginal value of the biomass as measured by the term $\lambda \cdot Y_e$. This means that it is not optimum to maximize instantaneous profits. According to (7.1), this temptation must be modified by the shadow value of all biomasses in the ecosystem. Equation (7.2), on the other hand, gives the equations of motion for the shadow value of the biomasses along the optimum utilization path.

Equations (7.1) and (7.2) contain the derivatives that describe how system variables respond to exogenous fishing effort changes. These derivatives are contained in the $(I \times I)$ Jacobian matrices Π_e, Y_e and G_x. G_x is the biological community matrix, as previously discussed. However, these two equations make it clear that the matrices Π_e and Y_e – which may be regarded as the economic community matrices – play in general just as important a role in the optimum management of ecosystem fisheries. Only if both matrices (as well as the community matrix) are diagonal will it be possible to run the fishery effectively on a single-species basis.

The matrix $Y_e = (\partial Y^i(e,x)/\partial e_j)$ represents the marginal catch of species i in response to increased fishing effort on species j. If there is no by-catch, this matrix will be diagonal, i.e.

$$\mathbf{Y_e} = \begin{pmatrix} Y^1_{e1} & 0 & \ldots & 0 \\ 0 & Y^2_{e2} & \ldots & 0 \\ . & . & . & . \\ 0 & . & \ldots & Y^1_{e1} \end{pmatrix}.$$

The marginal profit matrix, Π_e, is defined by:

$$\Pi_e = (\partial \pi^i/\partial e_j) = (\partial Y^i(\mathbf{e,x})/\partial e_j - \partial C^i(\mathbf{e})/\partial e_j).$$

So the typical element in Π_e represents the marginal profit in fishery i of increased fishing effort on species j. For this matrix to be diagonal there must be no by-catch and no interfishery cost effects. This means that in addition to a diagonal Y_e matrix, the C_e matrix must be diagonal as well, i.e. $\partial C^i(e)/\partial e_j = 0$ for all $i \neq j$.

Now, by eliminating the vector λ from necessary conditions (7.1) and (7.2), we obtain two sets of differential equations describing the solution to the maximization problem, namely (7.3) and

$$\dot{\lambda} = -\mathbf{1} \cdot \mathbf{Y_x} + \lambda \cdot (\mathbf{Y_x} + r \cdot \mathbf{I} - \mathbf{G_x}), \qquad (7.4)$$

where I is the identity matrix and the vector λ is defined by

$$\lambda = \mathbf{1} \cdot \Pi_e \cdot (\mathbf{Y}_e)^{-1}, \qquad (7.5)$$

where $(Y_e)^{-1}$ is the inverse of the matrix Y_e. This expression for the shadow values of biomasses is important. In principle, these shadow values can be calculated provided the fishery is moving along the optimum path.

The two sets of differential equations (7.3) and (7.4), along with the appropriate initial and transversality conditions, will in principle suffice to determine the paths of fishing effort and biomasses that solve the maximization problem (7). It is clear, however, that this system (especially equation [7.4]) is exceedingly complex. This has several important implications. First, the system may exhibit very complex dynamics. Therefore, even along the optimum path, the existence of multiple equilibria, bifurcations and even chaos cannot be ruled out (Montrucchio, 1992). Second, the system is in general very difficult to analyse even with high-powered numerical methods. Third, just obtaining one particular numerical solution may be a difficult task.

An equilibrium solution to this system is slightly more tractable. Imposing the equilibrium condition (i.e. $\dot{\lambda} = \dot{x} = 0$), we find after some rearranging:

$$\mathbf{1} \cdot \Pi_\mathbf{e} \cdot (\mathbf{Y_e})^{-1} \cdot [\mathbf{G_x} + \mathbf{C_e} \cdot (\Pi_\mathbf{e})^{-1} \cdot \mathbf{Y_x} - r \cdot \mathbf{I}] = \mathbf{0}, \qquad (8.1)$$

$$\mathbf{G(x)} - \mathbf{Y(e,x)} = \mathbf{0}. \qquad (8.2)$$

Expressions (8.1) and (8.2) yield 2I equations to solve for the 2I optimum equilibrium values of fishing effort (e) and biomass (x). The corresponding shadow values of the biomass (λ) can subsequently be calculated according to (7.5).

A number of observations concerning the equilibrium solutions are in order:

(i) The system may in principle exhibit many solutions, in which case, additional considerations are needed to determine the truly optimal equilibrium.
(ii) If some optimal equilibrium values of biomass are zero, as seems likely, the number of equations is reduced correspondingly (as is the number of unknowns).
(iii) The optimal dynamic paths between equilibria may be very complex. If there is more than one equilibrium, none can be globally stable. In fact, most equilibria may not even be locally stable.
(iv) In the single species case, $I = 1$, the system reduces to a nonlinear version of the usual modified golden rule equilibrium conditions for the fishery derived by Clark and Munro (1982).

$$G(x) + C_e \cdot Y_x/\pi_e = r$$

$$G(x) - Y(e,x) = 0.$$

(v) If all the Jacobian matrices (i.e. G_x, C_e, Y_e and Y_x) are diagonal, the system reduces to a collection of

Clark-Munro type single-species equilibrium conditions. In this case, the single-species theory applies even if the fishery is actually an ecosystem fishery. Notice, however, that this is a necessary condition: all these matrices must be diagonal. If even one is not, the single-species theory is not applicable. For instance, a diagonal community matrix (no biological interactions) is by no means a sufficient justification for employing single-species analysis.

(vi) The shadow values of biomass (λ) do not have to be positive. They might just as easily be zero or negative, as is made clear by equation (7.5). This makes perfect sense. The biomass value of a species that has little conservation or commercial value but is detrimental to the biomass growth of a very valuable species can hardly be positive. In fact, it is most likely negative, i.e. harvesting of that species should be encouraged beyond the point where marginal profits are zero.

These observations clearly have important implications for sustainability. First, the sustainability of all biomasses in the ecosystem is unlikely to be optimal. Second, sustainability in terms of ecosystem stability over time is by no means guaranteed. Depending on the initial conditions, the optimal path could easily be one of perpetual and even irregular cycles. Thus, it seems that in the ecosystem context the requirement of sustainability of all fisheries is much less appropriate than in the single-species case.

Ecosystem services

Having examined the optimum ecosystem fishery, I would like to say a few words about ecosystem services. As already stated, the vector $\lambda=(\lambda_1, \lambda_2, \ldots \lambda_I,)$ provides a measure of the economic contribution of the various species' biomasses to the value of the objective function V in (7). More precisely, λ_i equals the increase in aggregate fisheries profits or rents resulting from a small increase in the biomass of species i. Thus, λ_i is also equivalent to the price the receiver of all the fisheries rents (presumably society as a whole) would be willing to pay (or, in the case of a negative λ_i, would have to receive) for this small increase in the biomass of species i. In short, λ_i represents the marginal value of the services of species i to the user of the complete ecosystem.

The summation over all λs represents the value of the total contribution of all biomasses in the ecosystem to society. Thus, if all λs can be calculated, we would have a measure of the value of all ecosystem services as a whole. In this context, it is important to realize that the λ_is depend on the state of the ecosystem and its expected future evolution. Thus, their interpretation as the social value of the respective biomasses holds only along the optimum path of utilization. If the actual path is different, the social value of the biomasses would also be different (generally lower).

The appropriate equation for ecosystem services along the optimum path is given by equation (7.5). Alternatively, these services can be calculated on the basis of the differential equations in (7.4). Clearly, to apply either of these sets of equations requires a huge amount of information about the fishery and the underlying ecosystem. However, when property rights in the ecosystem services are sufficiently well defined, their market values tend to reflect the corresponding social values. In this case, therefore, the assessment of the social value of ecosystem services becomes more tractable.

Economic fisheries management instruments

In the previous section, optimum fishing effort was defined by the vector equation (7.1). For a particular fishery j, the relevant equation is:

$$\sum_{i=1}^{I} (Y^i_{e_j} - C^i_{e_j}) - \sum_{i=1}^{1} \lambda^i \cdot Y^i_{e_j} = 0. \qquad (7.1')$$

According to this equation, the "correct" application of ej takes account of its impact on all biomasses, all harvests and all cost functions.

In an unmanaged fishery, by contrast, fishing firms maximize their own profits. As is well established (e.g. Clark, 1976; Hannesson, 1993), this means in general that they pay insufficient attention to the shadow value of the biomass. In fact, for most fisheries with a reasonable number of participants, the fishing firms' imputed value of λ is not only too small, it is very close to zero (Arnason, 1990). This means that, instead of (7.1), the firms approximately follow the rule:

$$\mathbf{1} \cdot \Pi_e = 0, \qquad (9)$$

or its single species counterpart:

$$\sum_{i=1}^{I} (Y^i_{e_j} - C^i_{e_j}) = 0.$$

As a consequence, the fishing firms and the fishing industry as a whole behave suboptimally. This is the essence of the fisheries problem. Fishing firms do not take full account of their impact on growth in biomass and therefore they apply the wrong fishing effort. In the usual single-species fisheries models, aggregate fishing effort is generally too large and stocks are too small. In the ecosystem context, by contrast, fishing effort can just as easily be too small and species biomass too large.

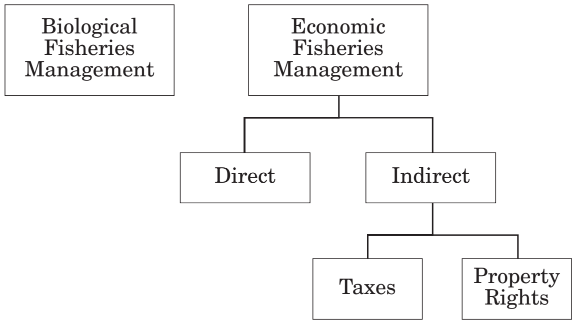

Figure 1. A classification of fisheries management methods.

To solve the fisheries problem, a great number of different management methods have been suggested and tried. Most of these can be conveniently grouped into two broad classes (Fig. 1): biological fisheries management and economic fisheries management. Economic fisheries management may be further divided into (i) direct restrictions and (ii) indirect management.

Biological fisheries management (mesh size regulations, total allowable catch, area closures, nursery ground protection, etc.) may conserve and even enhance fish stocks. However, they fail to improve the economic situation of the fishery because they do not impose the appropriate shadow cost of harvesting on the fishing firms as required by equation (7.1′). As a result, the fishing firms will respond to a successful biological management simply by expanding fishing effort, thus eliminating any temporary gains generated by the management measures.

Much the same applies to direct economic restrictions. Such restrictions take various forms (limitations on days at sea, fishing time, engine size, holding capacity of the vessels, etc.). These methods also fail to generate economic improvements because they do not impose the shadow cost of harvesting on the fishing firms. As a result, fishermen are still encouraged to expand uncontrolled inputs until all profits in the fishery have been wasted.

It is important to realize that setting and enforcing biological and economic fisheries restrictions is invariably costly. Usually, the costs are quite substantial. Because these measures do not generate any economic benefits, at least not in the long run, these costs represent a net economic loss. Consequently, we are driven to the conclusion that these fisheries management methods may be worse than no management at all!

The only management methods identified so far that, on theoretical grounds, have any chance of success are indirect economic ones. The most prominent of these are (a) corrective taxes or subsidies and (b) property-rights-based instruments such as individual transferable quotas.

Taxes on harvests

Comparison of equations (7.1) and (9) suggests that the imposition of unit harvesting taxes or subsidies (generally referred to as Pigovian taxes; Pigou, 1912) equivalent to the shadow value of biomasses λ will solve the fisheries problem. Under those circumstances, fishing firms will experience an additional marginal cost (or benefit) of effort equivalent to $\lambda \cdot Y_e$ as required by equation (7.1), and modify their behaviour accordingly.

There are serious practical problems with this approach, however. Most importantly, it has immense computational and informational requirements. First, there must be one tax rate for every biomass. In the ecosystem context this implies a high number of taxes. Second, the taxes are dynamic: they must be adjusted continuously over time if they are to be optimal. For these reasons, just calculating the taxes poses a formidable problem. In addition, there are apparently insurmountable problems to obtaining the information needed to do the calculations. The previous section gives the equation for the shadow value of biomasses, i.e. the appropriate tax rates on harvests, τ, as:

$$\tau = \lambda = \mathbf{1} \cdot \Pi_e(\mathbf{Y}_e)^{-1}, \qquad (10.1)$$

and its dynamics as

$$\dot{\lambda} = -\mathbf{1} \cdot \mathbf{Y}_x + \lambda \cdot (\mathbf{Y}_x + r \cdot \mathbf{I} - \mathbf{G}_x), \qquad (10.2)$$

Now, the pertinent information about the fishery is contained in the biological growth functions, G(x), the harvesting functions, Y(e,x), and the profit functions, Π(e,x). Therefore, expressions (10.1) and (10.2) make it clear that the fisheries manager must have instantaneous knowledge about everything in the fishery to be able to calculate the optimum tax. Clearly, this is beyond realism.

So, although taxes on harvest are theoretically attractive as a fisheries management tool, their application is subject to serious practical problems. Nevertheless, it should not be forgotten that taxes have the great advantage that any tax collection in excess of collection costs represents fisheries rents. Therefore, even in an environment of limited information, it is difficult to avoid improving the fisheries situation with a regime of corrective taxes. Therefore, taxes/subsidies remain an interesting option as a management tool in the ecosystem context.

Property rights

Individual quotas (IQs) and individual transferable quotas (ITQs) are probably the most widespread property rights system currently employed in ocean fisheries (Arnason, 1996). We will restrict our discussion to the following basic ITQ system:

(1) The fishing firms hold permanent fractions or shares ("share quotas") in the total allowable catch (TAC) for each species.
(2) Each firm's permitted catch of a given species ("catch quota") is defined as the multiple of its share quota for that species and the corresponding TAC.
(3) Share quotas as well as catch quotas are transferable and perfectly divisible.
(4) A central authority ("the fisheries manager") issues the initial share quotas and subsequently decides on the TAC for each species in the ecosystem at each point of time.

Note that this multispecies ITQ system requires that quotas be met exactly. This important point warrants an explanation. If a particular fishery is profitable, profit-maximizing firms will obviously not choose to hold unused catch quotas in this fishery. Therefore, the quota constraint only needs to be set as an upper bound. In the ecosystem context, however, optimum management will typically require the reduction of some stocks that are themselves not valuable but compete with (or prey on) valuable species. Such fisheries will not be privately profitable and the respective quota holders would like to avoid filling their quotas. Therefore, in the ecosystem context, the requirement that quotas (at least those for non-profitable species) be caught is needed.

Under this system, the quotas assume a market value because they are tradable. Let us refer to this set of prices at a point of time by the vector s. Clearly, s may be positive or negative according to whether the fishery is privately profitable or not. Therefore, the use of quotas for fishing implies an opportunity cost (or benefit) to the user just as a tax (or a subsidy). More formally, the marginal benefit of fishing effort is now:

$$\mathbf{1}\cdot\Pi_e-\mathbf{s}\cdot\mathbf{Y}_e=0. \qquad (11)$$

Thus, from comparison with equation (8.2), it is clear that, if quota prices s were equal to the shadow values of biomasses λ, the fishing firms, under an ITQ system, would act in a socially optimum fashion.

The market price of quotas obviously depends on the vector of TACs (Arnason, 1990). Therefore, by setting the appropriate TACs the authorities can induce the fishing industry to utilize the ecosystem in the optimum manner. The drawback is that selecting the correct vector of TACs (one for each species in the ecosystem) is a formidable problem. With regard to its computational and informational requirements it is formally equivalent to the taxation problem. However, under the ITQ system this problem can to a large extent be bypassed. The fundamental reason is that the information-processing ability of the market actually solves a good deal of the problem.

It may be taken for granted that all information about the biological and economic aspects of the fishery that the authorities can possibly obtain already exists within the fishing industry. First, the fishing firms have at least as much knowledge about their own operating conditions as the most determined fisheries authority could possibly hope to obtain. Secondly, because the state of the stocks and their ecosystem interactions constitute a major determinant of fishing firms' profitability, not the least in an ITQ environment, the fishing firms or, more generally, quota traders can be relied on to assemble and to make the best possible use of the available biological and ecosystem data. In fact, given a reasonably competitive industry, only those firms that efficiently collect and interpret all the relevant information will survive.

All this information is conveyed to the market in the form of offers and bids for quota. The resulting quota prices churned out by the market reflect the sum total of all the information available and the best aggregate judgement of all market participants. After all, market participants are betting their money on being right.

It can be shown (Arnason, 1990, 1998) that under fairly nonrestrictive assumptions the prices of permanent quota or, equivalently, quota shares reflect the present value of expected profits from using them. Moreover, the sum of all ecosystem quota values equals the expected profits from exploiting the ecosystem as a whole. More formally:

$$\Sigma_i s^i=\mathbf{1}\cdot\mathbf{s}=\int_0^{\infty}\mathbf{1}\cdot\pi\cdot\exp(-rt)dt=V, \qquad (12)$$

where s^i represents the price of (100%) quota share for species i and V represents the total value of all ecosystem fisheries.

Thus, under ecosystem ITQs, the task of the fisheries manager is greatly simplified. He only has to adjust the current vector of TACs for all species in the ecosystem until the total market value of permanent quota shares, which he can readily observe in the market, is maximized. The fisheries manager does not have to collect data on the fish stocks and the economics of the fishing firms. The firms themselves or, for that matter, market speculators can be relied on to gather and interpret the pertinent biological and economic information in the most efficient manner (barring, of course, possible problems stemming from the public-goods nature of information). This information will be reflected in quota prices. By selecting TAC vectors that maximize the total market value of share quotas, the fisheries manager, however, acts as if he had command of all this information. Because this management method is informationally extremely efficient, it may be referred to as the minimum information management (MIM) procedure.

Ecosystem fisheries management by means of ITQs has some interesting implications. For instance, negative TACs and negative quota prices for some species are quite possible and have a meaningful economic interpretation. For privately profitable fisheries, those that are normally observed in the real world, share quota price would be positive. On the other hand, the MIM procedure may well result in negative share quota prices for others. The reason is that the optimum ecological fisheries policy will usually require a reduction in the stock size of some species of fish that are themselves not valuable but prey on or compete with commercially valuable species. The quota price for these species would be negative, representing harvesting subsidies. This is not at all surprising. There are many parallels under the more developed property rights system ashore. Rewards for killing low-value predators such as mink and foxes and for the eradication of pests in general provide a case in point.

When share quotas prices are negative, profit-maximizing quota holders would clearly prefer not to spend economic resources catching their share quota. Therefore, the ITQ requirement that quotas be fulfilled must be imposed. Clearly, profit maximizers will only assume such an obligation for a payment. For this reason, the initial allocation of share quotas in a privately unprofitable fishery will normally require a payment or subsidy. The firms requiring the lowest subsidy, i.e. the most efficient ones, would normally be the recipients of these share quotas.

Another interesting feature is that optimum TACs for some species might be negative. A negative TAC means that the quota holders are under the obligation of adding to rather than extracting from the stock. Thus, it appears that ecological fisheries management by means of share quotas naturally accommodates fish stock enhancement as a dual to harvesting. Again, if a quota price for a negative total quota is negative it represents a subsidy for fish stock enhancement. That would occur in the case of socially optimum but privately unprofitable stock enhancement. An example would be the hatching and releasing of valuable marine fish into the ocean. Alternatively, stock enhancement may be privatelyprofitable. A case in point might be ocean ranching of valuable species such as scallops or salmon. For ecological reasons, the quota price would often be positive, indicating that the ocean-ranching firms would pay for the privilege of releasing fish into the ocean.

It should now be clear that there are four polar cases of ecological fisheries management in the ITQ framework (Table 1). Applying the MIM procedure to a given marine ecosystem will normally produce entries in one or more of the boxes identified. Notice, however, that a prerequisite for an entry with negative quota price is that there is at least one entry with a positive quota price. Hence, if the ecosystem is not useful at all, all share quota prices would be zero.

Table 1. Polar cases of total quota (TAC) and share quota prices (**s**)

	TAC	
s	Negative (stock enhancement)	Positive (fishery)
Negative	Unprofitable (subsidised releases)	Unprofitable (subsidised removal of predators/competitors)
Positive	Profitable (ocean ranching)	Profitable (commercial fishery)

It is important to realize that the MIM procedure actually compares the overall costs and benefits (as judged by the quota market) of any change in TAC, including stock-enhancement quotas. For instance, if stock enhancement of a given species was regarded as detrimental to valuable fisheries (presumably through ecological interactions), the share quota prices in these fisheries would decline, making it less likely that the MIM procedure would recommend the stock-enhancement TAC. For that to happen, the increase in the market price of the stock-enhancement share quota must exceed the decline in the market price of the share quotas of the other fisheries.

Obviously, changes in relative prices, environmental conditions and other variables would induce corresponding modifications in TACs. The same applies to new ecological or economic information in general.

Thus, we may conclude that an ITQ system, coupled with the MIM procedure, offers a flexible and promising approach to deal with the problem of ecosystem fisheries management. However, it by no means solves the problem. First, the effectiveness of the system hinges critically on the ability of the fisheries manager to enforce the quota constraint. This is always costly, often difficult and sometimes impossible. To the extent that the ITQs cannot be enforced, the system will not work. Second, it should be emphasized that the system will generally not yield the optimum fisheries policy, even when the system is perfectly enforced. What the MIM procedure maximizes is expected rents in the fishing industry. Economic rents are not necessarily the same as profits. More importantly, the rents maximized are those according to the expectations of the fishing industry and other traders in the quota market. These expectations are bound to be erroneous to some degree. Hence the MIM procedure will be correspondingly led astray.

Finally, an interesting by-product of the system is that the fishing firms are given an incentive to engage in their own fisheries research. Any company that will acquire better information about the pertinent ecological or economic relationships will be able to make money in quota trades. Thus, it appears that an ITQ system would facilitate a transition from a publicly funded research programme to a privately funded one. There are limitations to the desirability of this process, however. The most fundamental problem has to do with the public-domain nature of knowledge and information. This implies (Varian, 1984) that the private production of knowledge, i.e. scientific research, tends to be less than socially optimum. To a certain extent, it also subtracts from the ability of the private sector to outperform a centralized fisheries authority in the generation of fisheries information and knowledge. Therefore, it seems that even under an ITQ system, public fisheries research, or at least subsidies for private research, would still be called for.

Conclusion

Ecosystem fisheries are extremely complicated. Most ecosystems contain thousands of species and the number of potential biological and economic interactions increases exponentially with the number of species. Thus, ecosystems quickly become inscrutable, even from a static perspective. Ecosystem dynamics add to this complexity. Even with a few species, it is easy to generate multiple equilibria, bifurcations and even chaos in ecosystem models. In a real ecosystem, the scope for complicated dynamics is much greater. Consequently, they may be expected to exhibit strange dynamics, volatility and general unpredictability. Indeed, this seems to be the case in many ocean ecosystems.

Under these circumstances, the question is whether it is possible to manage ecosystem fisheries in a useful manner. The answer to this question is probably yes. The reason is that the outcome of unmanaged fisheries is so poor that, in spite of the complexity of ecosystem fisheries, it is not too difficult to improve upon the situation. The paper shows, however, that optimum management rules are very complicated. This means that it is very difficult to calculate optimum management paths, let alone to implement them. Therefore, anything close to an optimum utilization of an ecosystem fisheries may not be achievable in the near future.

A reasonable objective for ecosystem fisheries management, therefore, is the best possible management. Of the myriad of management measures that can be applied only two – taxes/subsidies and property rights – seem to be suitable in this respect. Of these two, property rights, when they can be applied, appear more promising. The fundamental reason is that the existence of property rights allows the market to generate prices that not only steer market participants to the common good, but also provide valuable management guidance to the fisheries manager.

The ITQ approach to ecosystem fisheries management seems to offer the promise of the best possible option. Under this system, the fishery will operate efficiently subject to the vector of TACs that has been set. Moreover, ITQ market prices provide the fisheries manager with the best possible information about the advisability of different TAC vectors. More precisely, under the usual assumptions concerning market efficiency, the TAC vector that maximizes the aggregate value of all outstanding ITQ shares also maximizes the present value of expected profits from the fishery.

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References

Arnason, R. 1990. Minimum information management in fisheries. Canadian Journal of Economics, 23: 630–653.

Arnason, R. 1996. Property rights as an organizational framework in fisheries: the cases of six fishing nations. *In* Taking Ownership: Property Rights and Fisheries Management on the Atlantic Coast. Ed. by B. L. Crowley. Atlantic Institute for Market Studies, Halifax.

Arnason, R. 1998. Ecological fisheries management using individual transferable share quotas. Ecological Applications, 8(1, Supplement): S151–159.

Clark, C. W. 1976. Mathematical Bioeconomic: The Optimal Management of Renewable Resources. John Wiley and Sons, New York.

Clark, C. W. 1985. Bioeconomic Modelling and Fisheries Management. John Wiley and Sons, New York.

Clark, C. W., and Munro, G. R. 1982. The Economics of Fishing and Modern Capital Theory: A Simplified Approach. *In* Essays in the Economics of Renewable Resources. Ed. by L. J. Mirman, and D. J. Spulber. North-Holland, Amsterdam.

Flaaten, O. 1988. The Economics of Multispecies Harvesting: Theory and Application to the Barents Sea Fisheries. Springer-Verlag, Berlin.

Flaaten, O. 1991. Bioeconomics of sustainable harvest of competing species. Journal of Environmental Economics and Management, 20: 163–180.

Hannesson, R. 1983. Optimal harvesting of ecologically interdependent fish species. Journal of Environmental Economics and Management, 10: 329–345.

Hannesson, R. 1993. Bioeconomic Analysis of Fisheries . Fishing News Books, Cambridge.

May, R. M., Beddington, J. R., Clark, C. W., Holt, S. J., and Laws, R. M. 1979. Management of multispecies fisheries. Science, 205(4403): 267–277.

Montrucchio, L. 1992. Dynamical systems that solve continuous-time concave optimization problems: anything goes. *In* Cycles and Chaos in Economic Equilibrium. Ed. by J. Benhabib. Princeton University Press, Princeton.

Pauly, D. 1982. Dynamics of multispecies stocks. Marine Policy, 6: 72–74.

Pigou, A. C. 1912. The Economics of Welfare. Macmillan, London.

Pontryagin, L. S., Boltyanskii, V. S., Gramkrelidze, R. V., and Mishchenko, E. F. 1962. The Mathematical Theory of Optimal Processes. Wiley-Interscience, New York.

Varian, H. R. 1984. Microeconomic Analysis, 2nd ed. W. W. Norton and Co., New York.