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Conflicting uses of marine resources: can ITQs promote an efficient solution?*

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This paper examines the allocation problem arising from conflicting demands for marine resource use by (i) commercial fishers, (ii) recreational fishers, and (iii) conservationists. It is shown that decentralised trading of individual transferable quotas (ITQs) is capable of an efficient allocation of resource use between the first two parties. In contrast, it is found that the standard ITQ system is not capable of performing the same ideal co-ordination between the conflicting interests of extractive users, that is, all fishers, and the non-extractive ones, that is, conservationists. The reason is that quota trades between individual fishers and conservationists are inevitably accompanied by (positive) externalities on both other fishers and conservationists. As a result, decentralised quota trades between these parties cannot be efficient. The fundamental economic observation is that quotas for conservation and for extraction constitute two different goods. It follows that a socially optimal market allocation of these two goods requires two prices instead of the single quota price in the standard ITQ system. Thus, to achieve efficiency, the ITQ system has to be extended to incorporate both types of goods. It is shown in the paper that if fishers and conservationists can organise themselves into groups, trades of conservation quotas between the two groups can in principle lead to fully efficient allocation. An interesting implication of this modified ITQ system is that the need for a fisheries authority to set the total allowable catch (TACs) disappears.

Key words: commercial and recreational fishing conflicts, conflicting use of marine resources, conservation quotas, fishing and conservation conflicts, ITQs.

1. Introduction

This paper deals with the situation where a fish stock, or, more generally, a renewable natural resource, has different uses. Specifically, we consider the situation where it has three different uses: (i) generating commercial harvests, (ii) generating recreational harvests, and (iii) generating conservation utility. Provided the resource is scarce, these different uses may be said to be rival or conflicting. Hence, a resource allocation problem arises. It is well-established that under a complete system of property rights and smoothly functioning markets, market trades may be relied on to bring about a Pareto-efficient solution (Debreu 1959). However, when property rights are limited or even non-existent – a situation typical of most marine resources – the outcome

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will generally not be anywhere close to being Pareto-efficient (Gordon 1954; Hardin 1968).

In recent years, tradable extraction rights, often referred to as individual transferable quotas (ITQs), have been widely implemented in fisheries in order to alleviate the common property problem. It has been demonstrated (Arnason 1990) that under fairly unrestrictive circumstances, appropriately designed ITQs are capable of maximising economic rents from a previously common property fishery. This theoretical result has received empirical support from the experience in a number of ITQ-managed fisheries around the world (Shotton 2000).

Similar approaches have been adopted in other natural resource uses, notably the tradable SO_2 emission quotas on the North American east coast. Also here, the empirical evidence supports the theoretical prediction that such instruments enhance efficiency in the use of the underlying natural resources (Schmalensee *et al.* 1998; Stavins 1998).

The application of ITQs to fisheries is designed to promote allocative efficiency in the use of the total allowable catch (TAC) amongst commercial users of the resource. What has not been explored is to what extent the ITQ instrument can also promote allocative efficiency when the resource in question has alternative uses, for instance, for direct consumption in the form of recreational fishing and/or conservation. As there are indications that these other uses are often of high value compared to that of commercial extraction, this represents a serious gap in our understanding.

The following constitutes an attempt to study the feasibility of employing ITQs to bring about the socially optimal balance (allocative efficiency) between resource conservation and extraction. The strategy is to specify a simple model of the situation and to explore the ability of the ITQ system to resolve the use conflict in a socially optimal way. If ITQs don't work in this simple setting, chances are that they won't in a more realistic setting either. If, on the other hand, ITQs do the job in the simple setting, there may be a reason for further exploration along these lines.

The paper begins by analysing the conflict between the three parties regarding the use of the fish resource. This appears as a disagreement about (i) total harvest rates, (ii) who should be entitled to harvest, and (iii) optimal stock levels. This is followed by Section 2 which explains how the ITQ system can resolve resource use conflict amongst commercial fishers. In Section 3, it is shown that the very same ITQ system can resolve the corresponding conflict amongst recreational fishers as well as the conflicting interests of commercial and recreational fishers in the socially optimal manner. All that is needed is that the ITQ system incorporates both groups on an equal footing. Section 4 explores to what extent the ITQ system can serve the same co-ordinating function for the conflicting interests of commercial and recreational fishers, on the one hand, and those of conservationists on the other hand. It is found that due to the external effects generated by conservation, the usual ITQ system will not perform this function well, although it may constitute an improvement over current arrangements. However, under a modified ITQ system where

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fishers as a group trade conservation quotas with conservationists as a group, there is a good chance that social optimality in resource use will be attained. Section 5 summarises the results of the paper and discusses its main implications.

2. Describing the basic situation: the conflict

Let us begin by modelling the basic situation. Among other things, this helps to clarify the nature of the conflict. Consider a fish stock or, for that matter, some other living marine resource whose dynamics are given by:

$$\dot{x} = G(x) - z, \tag{1}$$

where x represents the stock biomass and z the aggregate harvest. The function $G(x)$ is the biomass growth function exhibiting the usual dome-shaped properties (see, e.g. Clark 1976).

Consider a *commercial fishing industry* with an instantaneous aggregate benefit (profit) function:

$$\Pi(q, x), \tag{2}$$

where q represents harvest. The function $\Pi(q, x)$ is assumed to be monotonously increasing in biomass, x, and concave in both arguments. To make it economically interesting, we assume that there exist a biomass level such that the benefit function can be positive and is increasing in the harvest, q, up to a certain point.

Next, consider the *recreational fishery*. For our purposes it is immaterial whether this is a commercial recreational fishery with specialised firms offering fishing recreation to customers, or a pure recreational activity where individuals simply fish for their own enjoyment, or a combination of both. Let the aggregate benefit (utility/profit) function of this fishery be:

$$A(y, x), \tag{3}$$

where y represents the recreational harvest. This function, although different from that of the commercial fishery, is assumed to have the same basic shape. It is monotonically increasing in biomass, x, increasing in the recreational harvest level, y, at least up to a point, and concave in both arguments.

Finally, consider *conservationists* whose aggregate benefits are increasing in the biomass of the fish stock, at least up to a point. More precisely:

$$B(x). \tag{4}$$

The function $B(x)$ is, of course, a very simplistic representation of the benefits of the conservationists. For instance, they would usually be concerned about several environmental goods – not only one stock of fish. Moreover,

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many would argue that they would normally not be indifferent to the interests of the commercial and recreational fishers. The justification for restricting the conservationists' interests to the function in Equation (4) is that it allows us concentrate on the essence of the conflict.

Certain aspects of the above model are worth highlighting. First, note that the marine resource, x, is common to all the parties involved. None can be excluded from deriving benefits from it, and they all suffer the consequences of its reduction irrespective of who causes it. Thus, the biomass is what in economic parlance is called a non-excludable public good (Samuelson 1954, 1955). However, it is rival (scarce and can be reduced by use) and is therefore not a pure public good.

Second, note that commercial and recreational fishing represents extractive use of the fish stock (or more generally any marine resource) in the sense that it reduces the stock. By contrast, the conservation use of the resource is passive in this sense.[1]

Third, each of the three groups; the commercial fishers, the recreational fishers and the conservations, is in reality composed of a number of individual members. The preferred harvests and stock size of these members generally do not coincide. For instance, the interests of the extractive users, the fishers, are diametrically opposite in the sense that each one of them is negatively affected by the harvesting of others. This is the fundamental stock externality in fisheries much discussed in the literature on fisheries economics (Turvey 1964; Smith 1969). It is a consequence of this negative externality that each fisher would prefer all other fishers to completely refrain from harvesting. For the conservationists, the externality situation is often reversed. Each conservationist may derive benefits from the conservation actions of other conservationists. So, at least up to a point, the externality effect is positive. However, as in the case of fishers, different conservationists would generally want different biomass stock sizes. So, also within the group of conservationists there generally is conflict.

To make headway, we assume, for the time being, that each group has somehow resolved their internal contradictions – presumably by adopting a policy that maximises the total benefits to the group – and acts as one unit. On this basis, we assume that each group seeks to maximise the present value of its flow of benefits over time. For simplicity we assume, moreover, that all have the same rate of discount, r.[2]

It is now straight-forward to demonstrate that the desired stock size of the three groups, will generally not be identical. Moreover, each would prefer the extraction rate of the other parties to be zero. In other words, their desired use of the resource will generally conflict. To see this we only need to solve

[1] It is, of course, conceivable that activities often associated with conservation such as observation also impact on the fish stocks. The basic approach of this paper is easily generalised to incorporate this factor.

[2] Actually, by reference to basic market principles, if financial markets are perfect, this should be the case.

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their respective maximisation problems. This is done in Appendix 1. In a non-trivial (positive biomass) equilibrium, the desired biomass, x, and harvesting levels for the three parties acting as groups are as follows (see Appendix 1):

Commercial fishers:

$$\begin{aligned} &G_x + \Pi_x/\Pi_q = r, \\ &G(x) = q, \\ &y = 0. \end{aligned} \tag{5}$$

Recreational fishers:

$$\begin{aligned} &G_x + A_x/A_y = r, \\ &G(x) = y. \\ &q = 0. \end{aligned}$$

Conservationists:

For the conservationists, the situation is slightly more complex. There are two distinct cases of apparent relevance. In the first case the conservationists prefer the maximum biomass nature allows or a greater biomass. In that case the optimality conditions are:

$$\begin{aligned} &G(x) = 0, \\ &y = q = 0. \end{aligned} \tag{6}$$

The former of these expressions sets the desired biomass at the virgin stock equilibrium and the latter expresses the desire that all harvests be zero. Note that in this case the marginal benefits of biomass to the conservations, that is, $B_x(x)$ may well be positive. This means that the conservationists may prefer a biomass larger than the one nature can provide.

In the second case, the conservationists want a biomass less than the maximum attainable one. In that case, their optimal biomass and harvests are defined by:

$$\begin{aligned} B_x(x^*) &= 0 \\ G(x^*) &= q + y, \end{aligned} \tag{6'}$$

where x^*, a biomass less than the virgin stock equilibrium, denotes the desired biomass by the conservationists. So, in this case the conservationists want a certain ‘culling’ of the biomass. The reason for that is for our purposes irrelevant. Note, that, at least in this simple representation, they don’t care whether the culling is by recreational or commercial fishers.

The first two expressions in the optimality conditions for commercial fishers, Equation (5) above, are well known in the fisheries economics literature as the equilibrium conditions for the optimal fishery (Clark and Munro 1975;

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Arnason 1990). The term Π_x/Π_q, which plays some role below, is referred to as the marginal stock effect by Clark and Munro (1975). It basically expresses the marginal equilibrium contribution of added stocks to instantaneous harvest ($\Pi_x/\Pi_q \approx \partial q/\partial x$). Given profit maximisation, the marginal stock effect is non-negative and its effect is to increase the equilibrium biomass compared to what would otherwise be the case. The third equation, $y = 0$, represents the extension of the standard bio-economic fisheries model to the case, where recreation fishers are also extracting from the fish stocks. It expresses the common desire of commercial fishers that the recreational harvest be zero.

The optimal equilibrium conditions for the recreational fishers exhibit the same formal structure as those for the commercial fishers. This is not surprising. Both activities are qualitatively the same, extraction of fish to generate benefits. The main difference is that the marginal stock effect for the recreational fishers, A_x/A_y, would generally be different from that of the commercial fishers. Hence, so would their optimal equilibrium harvest and biomass. Needless to say, recreational fishers would want commercial harvest to be zero as expressed by the condition $q = 0$.

Expressions (6) and (6′) for the conservationists are more novel and warrant some explanation. First, note that both equation systems are recursive. The first equation in each set gives the conservationists' desired biomass level while the second equation defines the aggregate harvest needed to maintain that biomass level. The desired biomass level occurs, not unexpectedly, where the marginal benefits of biomass to the conservationists are zero (as in the second case) or positive (as possibly in the first case). The desired biomass level depends entirely on the conservationists' tastes. It is quite conceivable; for instance, that the conservationists' desired biomass level exceeds the carrying capacity of the environment (the first case) in which case, the conservationists would like to see stock enhancement. It is also quite possible that the conservationists, possibly for ecosystem reasons, would like to see the biomass level reduced from the virgin stock equilibrium in which case they would want some harvesting (the second case). It is even possible that the conservationists would like to see the biomass at zero indicating that they regard the species as a pest.

It is obvious that only very coincidentally would these optimality conditions for the three groups yield the same biomass and harvesting levels. For instance, the conservationists might, according to the above, want the biomass at the virgin stock equilibrium and no harvesting whatsoever. The commercial and recreational fishers would only agree to this if neither of them could gain benefits from harvesting at that biomass level, that is, extraction would not yield any benefits even at a high biomass level. If either commercial fishers or recreational fishers can gain benefits from fishing, they would want a smaller equilibrium biomass than the conservationists. However, they would normally not want the same equilibrium biomass. Moreover, commercial fishers would generally not want any harvest by recreational fishers and vice versa. A numerical example of these conflicting desires is worked out in

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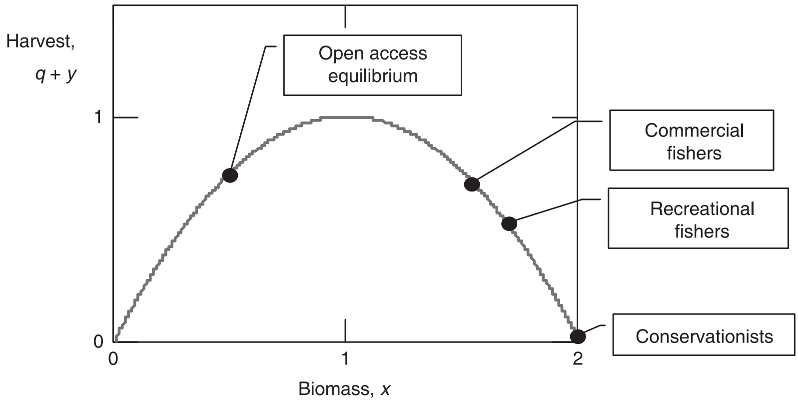

Figure 1 Desired biomass and harvest.

Appendix 2. One possible outcome is in terms of sustainable or equilibrium biomass and harvest is illustrated in Figure 1.

On this basis, it seems clear that when it comes to marine use, the objectives of commercial fishers, recreational fishers and conservations are generally in direct conflict. Each group would normally want a different equilibrium biomass and harvest. Moreover, whatever the overall level of harvest, the commercial and recreational fishers would like to see the harvest of the other group as zero. These conflicting interests will of course be somehow worked out by society. The important thing is to do so in the socially optimal way.

3. ITQs in commercial fishing

ITQs have become widely and apparently successfully employed in the world's fisheries. According to a recent count (Arnason 2006) over 10 major fishing nations use ITQs as the main or a major component of their fisheries management system, and between 10 and 15 per cent of the global ocean catch is taken under ITQs. Although several other forms of fisheries property rights, such as sole ownership, TURFs, community rights and so on, exist, ITQs and their non-tradable counterpart, IQs, are by far the most widely used property rights instruments in the world's fisheries today.

Many variants of the ITQ system are possible. In this paper we assume the following ITQ system: A TAC applies at each point of time. Individual fishers hold rights to harvest a fraction of this TAC. These rights, or quota shares, are perfect property rights, that is, they are fully exclusive, secure, permanent and tradable. It is of importance to recognise, however, that the ITQs are but harvesting rights. As such they are fairly weak property rights in the underlying natural resources, namely the fish stocks and their ocean environment (Arnason 2000).

The detailed theory of the workings of this ITQ system is technically somewhat involved. Fortunately, it is possible to explain the essence of the

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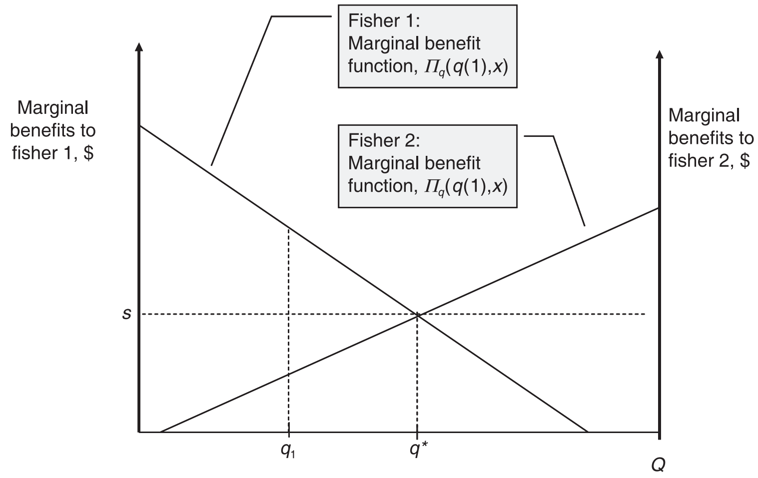

Figure 2 Optimal allocation of resource use (fishing).

theory in a simple manner. For the interested, the key nuts and bolts of the theory are explained in Appendix 3.

As shown in Appendix 3, the ITQ system, virtually automatically, generates allocative efficiency amongst the fishing firms. That is to say, whatever TAC is set will be fished by the right number of the most efficient fishing firms. The reason for this is simple. The ITQs represent a tradable property. Therefore, if a less efficient firm holds an ITQ, it will find it profitable to sell or rent a part of it to a more efficient fishing firm and vice versa. These trades will continue until either the firm has sold all its quotas and leaves the industry, or it cannot find more efficient fishing firms to trade with. This applies to all firms at all times. Thus, in this trading equilibrium, only the most efficient firms will be engaged in harvesting. Moreover, the marginal benefits of quota use will be equal across firms active in the industry. This common marginal benefit is also the equilibrium price of quota.

Note that this allocative efficiency of the ITQ system happens in a totally decentralised manner. It is brought about by individual fishers trying to maximise their own benefits. As already explained, these trades must always be in the direction of more efficient allocation and they do not halt until no further efficiency can be obtained.

We can illustrate this basic allocative efficiency of the ITQ system with a simple diagrammatic device, which has the added advantage that we can also use it to illustrate the optimal allocation of harvesting rights between the three groups later. Consider the allocation of harvests between any two fishers. Assume these fishers hold a certain volume of quotas, $q(1)$ and $q(2)$, say, the sum of which is Q. For concreteness, this Q may be regarded as the *TAC*. Let us refer to these two marginal benefit functions as $\Pi_q(q(1), x)$ and $\Pi_q(q(2), x)$, respectively, and draw them as in Figure 2. In this figure, the marginal benefits to fisher 1 are measured on the left-hand vertical axis and

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the marginal benefits to fisher 2 on the right-hand vertical axis. Any point on the horizontal axis represents a given allocation of harvests between the two fishers. Thus, for instance, the point q_1 on the horizontal axis represents the allocation of q_1 units to fisher 1 and the remaining $(Q - q_1)$ units to fisher 2.

Now, it is easy to establish that the economically optimal allocation of the total harvesting quantity, Q, between the two fishers occurs at the point q^*, where their two marginal benefit curves intersect. For instance, letting fisher 1 harvest a little bit more and fisher 2 a little bit less, that is, moving slightly to the right of q^* entails less gains to fisher 1 than there are losses to fisher 2. Thus, this modification cannot be economical. Corresponding arguments apply to letting fisher 2 harvest a little bit more and fisher 1 a little bit less.

It is similarly easy to establish that under the ITQ system, q^* is precisely the point to which trade between the two fishers will bring them, irrespective of their initial holdings of quotas. To see this, we only have to note that whenever they are not at q^*, they will both benefit from trading their quotas toward q^*. At this point, the trading price is s, which, in turn, equals the marginal benefits to each fisher exactly as demanded by allocative efficiency. It is worth observing that the area $s \cdot Q$ in Figure 2 is a measure of the resource or fisheries rents in this fishery.

Note that there is no reason for the optimal point q^* to correspond to positive harvests for both fishers. If one of them, for example, fisher 1, is very inefficient relative to the other, his marginal benefit curve will be very low and fisher 2 will take all the all the allowable harvest.

Clearly, this argument can be extended to any number of fishers. Thus, by this diagrammatic device, we have essentially shown that the ITQ system results in efficient allocation of the TAC between all fishers.

Thus, under the ITQ system defined, the fishery will operate as efficiently as possible, for any given TAC. This strong theoretical result seems to be verified by the experience of ITQ systems around the world (Wilen and Homans 1994; Arnason 2006). The problem, however, is to select the right TAC. This task is usually allocated to fisheries authorities. Their problem is select TACs such that the fishery follows the optimal path toward equilibrium. It is straight-forward to define this path analytically (see Appendix 3). To find it in practice, however, is a different proposition, primarily because of scarcity of the appropriate information. Provided markets work reasonably well, it can be shown (Arnason 1990) that the optimal TAC at each point of time is the one that maximises the overall quota values. Thus the problem of finding the right TAC is reduced to selecting the one that maximises the value of quota shares. Note that it is only because of restrictive TACs that quota rights assume market value. If the TAC (Q in Figure 2) is too high both fishers would move to a point where their marginal benefits from harvests and thus also the quota prices are zero. This position is identical to the open access or common pool position of the fishery.

In addition to being economically efficient, the ITQ system resolves (or at least redefines) the fundamental conflict between fishers for catch. With the

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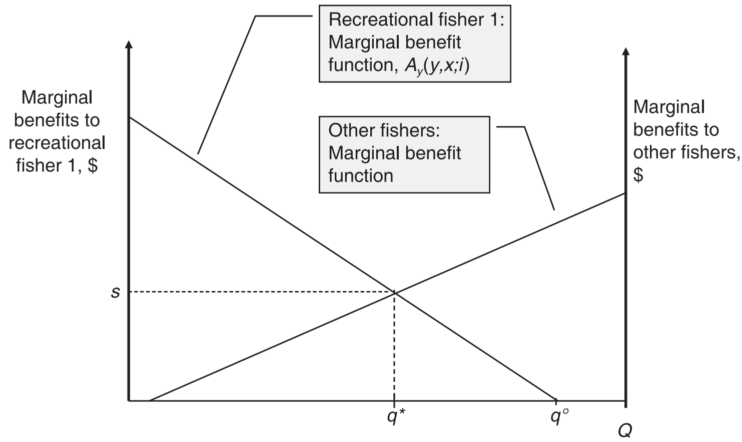

Figure 3 Commercial and recreational fisheries.

help of the social institution of property rights, namely ITQs, the conflict is transformed into market trades. Those who want more catch do not have to fight for it. They can simply buy the rights in the market place.

4. Reconciling commercial and recreational fishing under ITQs

We have seen how ITQs can, in an economically efficient way, harmonise conflicting demands for harvests by commercial fishers. What about other extraction demands from, say, recreational fishers? The answer is that these demands can also be completely reconciled with each other as well as with those of commercial fishers within the framework of the ITQ system. The reason is simple. Recreational demands for harvests are analytically identical to commercial ones. Recreational fishing is extractive in exactly the same way as commercial fishing and recreational fishers have benefit functions qualitatively the same as those of commercial fishers. As a result, recreational fishers are for analytical purposes just like additional commercial fishers. They should harvest to the extent that their marginal benefit functions exceed those of the commercial fishers already active in the fishery. By the same token, for any given TAC, less beneficial recreational fishing should give way to commercial fishing.

Under a joint ITQ system, that is, an ITQ system comprising both commercial and recreational fishing, this is exactly what will be the outcome. If a recreational fisher gets more benefits from fishing than a commercial fisher, it will be in the interest of both to trade commercial quotas to the recreational fisher and vice versa. This is illustrated in Figure 3 in which fisher 1 is a recreational fisher and fisher 2 represents the remaining group of all other fishers, commercial as well as recreational.

The optimal allocation of harvests is q^* and as argued in Section 2 and formally shown in Appendix 4, this is going to be brought about by quota trading. At this optimal point the marginal benefits to both the recreational

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fisher and the commercial fishers are the same and equal to the market price for quotas, s. This market price, however, would normally differ (be higher) from the one applying if only the commercial fishers were included in the quota system. The reason is increased demand for quotas. Note, moreover, that, as before, it doesn't matter for allocative efficiency how the quotas are initially held. Quota trades will bring them to the most efficient point. Finally, note that as before the optimal allocation does not necessarily have to imply that both sectors, the commercial and the recreational, are active in the industry. If one of them is sufficiently efficient, the other would be eliminated from active participation in the fishery.

Due to their practical importance, we state the above findings formally as Result 1:

Result 1

Under a joint ITQ system, the allocation of catch between commercial and recreational fishers will be socially optimal.

Result 1 provides the basic justification for using a joint ITQ system to resolve conflicting demands for harvest between recreational and commercial fishers. A formal proof of the result is presented in Appendix 4.

It is important to appreciate that without the joint ITQ system or some equivalent form of management, the resource use allocation between the two groups will often be highly inefficient. For instance, if recreational fishers are not constrained in the rextraction, they will operate at a point where their marginal benefits are zero (q° in Figure 3). This position, corresponding to the common pool equilibrium, can be extremely wasteful. How wasteful it is depends primarily on the attractiveness of the fishery to recreational fishers. The more attractive it is the greater the waste. Similar results apply to arbitrary restrictions, presumably set by fisheries authorities, on recreational harvesting. Besides creating its own inefficiencies as recreational fishers try to overcome or bypass the constraints, the harvesting restrictions are highly unlikely to be set at the correct level.

The above ignores the setting of the optimal TAC level. With the addition of the recreational sector, the optimal TAC, that is, the one that maximises the value of the total fishery would generally be changed. More specifically, as shown in Appendix 5, with commercial and recreational fishing (but no conservationists), the optimal equilibrium conditions for the fishery will be defined by the conditions:

$$\begin{aligned} &G_x + (\Pi_x + A_x)/\Pi_q = r, \\ &G(x) = q + y. \\ &\Pi_q = A_y. \end{aligned} \tag{7}$$

Where, as before, $\Pi(q, x)$ is the benefit function of the commercial fishing industry and $A(y, x)$ the benefit function of the recreational fishery. The variables

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q and y denote the harvest of the commercial fishery and the recreational fishery, respectively, the sum of which represents the optimal TAC.

Comparing this new set of conditions to the one for the fishery only, Equation (5) above, shows that the presence of the recreational fishery alters the marginal stock effect – it is now $(\Pi_x + A_x)/\Pi_q$ instead of Π_x/Π_q. So, the new marginal stock effect takes account of the benefits of the biomass to the recreational fishers as well to the commercial fishers. This means that in general both the optimal biomass and TAC will be altered. If both industries should operate, the combined optimal biomass will be between the ones the two groups would have selected for themselves. Normally, if the recreational fishers value the stock more highly than the commercial fishers, the TAC will be reduced compared to what the commercial fishers would like and vice versa. The rule for setting the optimal TAC is basically unchanged. It should be set so as to maximise the total value of all quota shares, recreational as well as commercial. Of course, as already shown in Figure 3 (and formally in Appendix 4), in optimal equilibrium, the marginal benefits of harvest to fishers, Π_q, equals that of the recreational fishers, A_y.

5. Reconciling fishing and conservation under ITQs

We have now seen that combining recreational and commercial fishers within the ITQ framework leads to efficient allocation of harvesting amongst them. In this section, we turn our attention to the conflicting interests of fishers and fish conservationists. Our basic question is whether and to what extent ITQs can also bring about an efficient allocation of resource use between these groups.

A formal analysis of the capabilities of ITQs in this context is somewhat involved and lengthy. Therefore, it has for the most part been relegated to Appendix 6. The socially optimal joint utilisation is derived in Appendix 5. The fundamental result of the analysis in these appendices is that the usual decentralised ITQ system will not bring about the socially optimal allocation of resource use.

The reasons for this outcome, although complicated to derive formally, are not difficult to understand. Within the ITQ system, conservationists buy quotas to prevent them being fished. Thus, the effective TAC is altered and a stock-externality is reintroduced into the system. It is, however, not reintroduced in the same form as before. Fishers are still constrained by their ITQs which they cannot exceed. Thus, the negative stock externality, which fishers impose on each other, continues to be kept in check by the ITQ system. However, with conservationists buying (and possibly selling), quota shares, the path of the biomass over time, which under the usual ITQ system is exogenous, becomes endogenous. Each trade of quotas between fishers and conservationists imposes an externality (a positive one if fishers are selling and a negative one if they are buying) on all other fishers. As individual fishers do not take this into account, they will offer their quota shares at too high a price to the conservationists than would be socially optimal.

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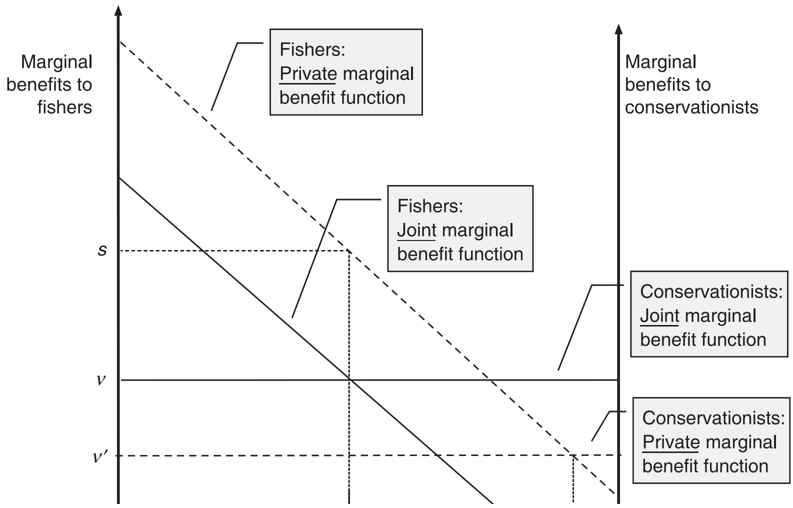

Figure 4 Fishing vs. conservation allocation.

This, however, is not all. The stock of fish is a common good to all conservationists. So, if a conservationist buys quota to keep it from being fished, he is not only benefiting himself, he is generating benefits for all other conservationists (in addition to the benefits to the fishers discussed above). This is like the fisheries common property problem in reverse. When one conservationist buys fishing quota for conservation, he is imposing a positive externality on all the other conservationists. This externality, he doesn't take into account. As a result, each conservationist offers a lower price and buys fewer fishing quotas than would be socially optimal. This is, of course, diametrically opposite to the fisheries situation where the externality, the extraction-externality, say, is negative and each fisher does too much fishing.

We can illustrate what is going on in a way similar to what we did in the case of the commercial and recreational fishers. In Figure 4, the TAC has been set at Q. The fishers' share of the TAC is measured in the rightward direction along the horizontal axis and the conservationists' share in the leftward direction from Q. Note that the effective TAC, that is, the part of Q that is actually going to be fished, is represented by the fishers' share and the un-fished part by the conservationists' share. Thus, the allocation of the official TAC, between the fishers and the conservationists now sets the effective TAC. In other words; the actual aggregate harvest is determined endogenously within the ITQ system! In what follows we will for convenience simply refer to the effective TAC as $\bar{Q}$. The fishers' marginal benefits of $\bar{Q}$ are measured along the left-hand vertical axis. The conservationists' marginal benefits of $\bar{Q}$ are measured along the right-hand vertical axis.

In Figure 4, the fishers' joint marginal benefit curve of Q, that is, the one that results from solving their joint maximisation problem, is drawn as the

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solid downward sloping curve. The conservationists' joint marginal benefit curve, that is, the one that maximises their total benefits, is drawn as the *solid* horizontal curve. This curve is horizontal because, as previously explained, conservation benefits are assumed to depend on the level of biomass, which is a fixed quantity at any point of time. It is useful to note that the two marginal benefit curves can also been seen as supply and demand curves. They represent for the two parties the desired quota, $\bar{Q}$, at any price. Whether the curves represent supply or demand depends on the initial allocation of quota rights. Thus, for instance, if the fishers hold all the quota rights (the Q is allocated to them), their marginal benefit curve represents their supply of conservation quotas and vice versa.

From Figure 4, it is obvious that the jointly optimal effective TAC is at $\bar{Q}^*$. The corresponding transaction price of conservation quotas between fishers and conservationists is v. Unfortunately, however, as discussed above, this will not be the outcome under a decentralised ITQ system. In deciding on quota trades, individual fishers and conservationists are only concerned with their own private benefits and costs and do not take account of the external benefits of increased conservation quotas into account. In other words, the marginal benefit curves of individual fishers and conservationists will underestimate the true benefits. As a result, individual fishers (be they commercial or recreational) will demand (offer) too high a price for selling quotas to (or buying from) conservationists. Thus, the private marginal benefit curve of fishers (aggregated over all fishers) will be higher than the jointly optimal one as illustrated with the dashed benefit curve in Figure 4. Similarly, conservationists will offer too low a price for buying quotas from (or selling to) fishers. Thus, the private marginal benefit curve of conservationists (aggregated over all conservationists) will be less than the jointly optimal one as illustrated by the dashed curve in Figure 4. As a result, under the decentralised ITQ system, fishing will take place at $\bar{Q}^{\circ}$ instead of $\bar{Q}^*$ So, there is less conservation than would be socially optimal. Indeed, depending on the conservationists' private preferences there might not be any conservation, whatsoever.

So, the usual decentralised ITQ system will not result in the optimal allocation of resource use between fishers (more generally extractors) and conservationists (more generally passive users). In this sense the system fails. We express this finding as Result 2.

Result 2

Under a joint decentralised ITQ system, the allocation of harvesting rights between fishers and conservationists, that is, the level of conservation will generally not be socially optimal.

As a consolation, note that although the ITQ system fails to attain social efficiency, it to can only represent a social improvement compared to not

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allowing conservationists to participate in the ITQ system at all. If conservationists value the resource higher than fishers, the only effect can be toward less fishing and more conservation as is made clear by Figure 4. The problem is that the improvement is not great enough.

Now, instead of the usual decentralised quota trades, let us assume that both parties, fishers and conservationists, act as one entity with regard to trade of quota shares between the groups. This of course means that the trading quantity and the quota price is a matter of bilateral negotiation. However, in this situation, where rights are well defined by virtue of the ITQ system, there is a high likelihood that the parties will agree on the harvesting solution that maximises their joint benefits (Coase 1960). Under those circumstances it is shown in Appendix 6 that the actual harvesting quota and biomass paths will be described by exactly the same set of differential equations as the joint optimal solution (see Appendix 5).

So, in this form of centralised ITQ system, where both parties, the fishers and the conservationists, internalise their respective conservation externalities by acting as groups, ITQ trades between the groups are indeed likely lead to the socially optimal harvesting quotas at each point of time. We express this formally as Result 3.

Result 3

Under the conditions specified (i.e. an ITQ system where fishers as a group, trade conservation quotas with conservationists as a group and a bargaining equilibrium has been struck) the allocation of resource use between extraction and conservation will be solved.

The alternative to taking account of conservation interests via the above-described extended ITQ system including both fishing and conservation quotas, is to either ignore conservation sentiments or take account of them by reducing the official TAC for fishers. Neither is likely to result in an efficient allocation. The latter, which has a greater potential, would generally run afoul of informational problems. To set the appropriate TAC requires not only the immense information necessary to determine the benefit function of fishers but the even more difficult problem of obtaining information about the benefit functions of the conservationists. So, even if the extended ITQ system does not work perfectly, it is very likely to be superior to any allocation between conservation and fishing which the government might determine.

Apart from the basic results expressed in Results 2 and 3, the analysis suggests a number of interesting and potentially important results: First, in an ITQ system comprising both fishers and conservationists, the TAC set by the fisheries authorities, that is, Q, may well be irrelevant. This certainly happens, when both parties are active in the quota market. The reason is that trades between the conservationists and the fishers actually determine

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the effective TAC, that is, the actual aggregate catch. In this sense the official TAC is irrelevant. It immediately follows that, under these circumstances, the usual function of the fisheries authorities, that is, setting the TAC, is no longer necessary. They do not even have to set the initial TAC. All that is necessary is to allocate the initial quota shares, $\alpha(i)$s. Given this, the interested parties, provided they act as groups, are in a position to set the most beneficial overall effective TAC. One should add however, that in the resulting bargaining game, the usual problems of strategic behaviour, asymmetric information, and so on, might (and probably will) arise. The fundamental practical point, however, is that the fisheries authorities in setting a TAC or allocating rights between groups of fishers and conservationists are subject to these same problems as well as several others.

Second, it doesn't matter for the eventual harvesting outcome to which party the initial allocation of quota shares, or more generally fishing rights, is made. If the fishers receive all initial quota shares, the conservationists have to buy from them, and if the conservationists receive the quota shares, the fishers will simply have to buy the harvesting rights from them. Obviously, however, it makes a great deal of difference for the distribution of income which party gets the rights.

Third, under the joint ITQ system, where fisheries and conservationists act as groups, there are basically two different types of quota shares; conservation quotas and fishing quotas. Conservation quotas are the ones traded between fishers and conservationists and subject to bilateral negotiation. Fishing quotas are the ones that fishers trade amongst themselves. Being different goods, these two types of quotas would normally not have the same market price. This is illustrated in Figure 4, where s refers to the price of fishing quotas and υ to the price of conservation quota, both evaluated at the optimal harvest point $\bar{Q}^*$.

In Figure 4, the fishing quota price, s, is higher than the conservation quota price, υ. Indeed, in Appendix 6 it is shown that if fishing takes place, the price of the fishing quotas will always be greater than the price of the conservation quotas. This is easy to understand. By trading fishing quotas to conservationists, fishers lose a value equivalent to the price of fishing quotas but gain in terms of increased future stocks. Therefore, *acting as a group*, they are willing to engage in such a trade at a lower price than the price of fishing quotas. Alternatively, when fishers buy conservation quotas from conservationists, they again gain a value equivalent to the price of fishing quota at that time, but lose in terms of reduced stocks of fish. Therefore, they are only willing to engage in such a trade as a group if the price of the conservation quota is less than that of the fishing quota.

Under a decentralised ITQ system, no one knows whether quotas are for conservation or fishing. Hence there is only one quota good and one quota price. In Figure 4, this common quota price is represented by υ' applying to harvest of $\bar{Q}^{\circ}$. Obviously, υ', must be lower than υ.

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6. Conclusions

A properly designed and operated ITQ system will resolve conflicts in resource use amongst commercial fishermen in the socially optimal way – conditional, of course, on the TAC that has been set. As shown in this paper, including recreational fishing in the same ITQ system will produce the socially optimal allocation of resource use across all fishers, commercial and recreational. This is potentially a very useful result. Note, however, that it is derived assuming perfect and costless enforcement of the ITQ system. Obviously, costly and imperfect enforcement might imply certain modifications of the result. In certain fisheries it may, for instance, turn out that the enforcement of ITQ restrictions on recreational fishers is prohibitively costly.

Using the ITQ system to resolve fishing (extraction) and conservation conflicts in not as straight-forward. The fundamental reasons for this, as explained in the paper, are the external effects associated with conservation. First, allowing purchases of quota shares for conservation purposes within the ITQ system reintroduces a part of the stock-externality, which the ITQ system for fishers was designed to neutralise. Second, conservation is inherently a public good. One conservationist's purchase of fishing quota for conservation purposes impacts all conservationists. Thus, it generates an externality which is usually positive.[3] It follows from these externalities that both the supply by individual fishers of quotas for conservation purposes and the demand by individual conservationists will be different, usually less, than would be socially optimal. Consequently, under decentralised quota trades, the level of fishing will usually be higher, and that of conservation lower than would be socially optimal.

So, the conventional (decentralised) ITQ system will not allocate resource use optimally between the conflicting demands of fishers and conservationists. It is important, however, to realise that this is not an absolute failure. It is only a relative failure compared to the optimal. Including conservationists in the ITQ system will generally lead to some, albeit too little, quota purchases for conservation purposes compared to the alternative of excluding them from quota purchases.

It turns out, however, that a certain modification of how the ITQ system can operate has a good chance to lead to an efficient allocation of resource use between fishers and conservationists. The modification is briefly that the usual (decentralised) ITQ system applies within the group of fishers (extractors), but trades between fishers and conservationists are centralised in the sense that they can only be conducted between the two parties as groups.[4] It is shown in the paper that under this system, the allocation of resource use will be identical to the optimal, at least in bargaining equilibrium. Moreover, this

[3] Actually, the same applies to the selling of conservation quotas to fishers, except in that case the externality imposed on other conservationists would normally be negative.

[4] Note that to the extent that conservation is a public good, there is no need for an ITQ system between conservationists. If conservation has some private good aspects that could easily be taken care of by a separate ITQ system for conservation quotas amongst conservationists.

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result applies both in stock equilibrium and along dynamic adjustment paths. The reason for this is fairly obvious. By acting as a group, fishers internalise the stock-externality of setting quotas aside for conservation purposes. Similarly, by acting as a group, the conservationists internalise the conservation externality. In other words, by acting as groups both parties effectively turn the public good attribute of conservation into a club good (Buchanan 1965). Hence, their supply and demand for conservation quotas will be increased toward what would be optimal for each group as a whole.

So, under this modified ITQ system, allocation of conflicting resource use between fishers and conservationists will be optimal or close to it. Similar result should apply to allocation of resource use between extractors and passive users in general. It is important to realise, however, that this is a theoretical result. To actually set up or implement the modified ITQ system is not a simple undertaking. First, the associations of the two groups must be established. This is obviously not straight forward. Second, the two associations must be organised in a way that generates incentives to maximise the total benefits of their members. This, as is well known, is a major problem in organisational economics (Williamson 1970; Furubotn and Richter 2005). Third, the two associations have to find a way to obtain reliable knowledge of their members' preferences. This is generally a non-trivial problem but certain preference revealing mechanisms exist to do this (e.g. the Groves–Vickrey mechanism; Vickrey 1961; Groves 1973).

An interesting and potentially very important by-product of the modified ITQ system is that it generates an effective TAC, that is, the real harvest level. Fishers or, more generally, extractors bargain with conservationists or, more generally, passive users about the effective TAC. The outcome, in bargaining equilibrium, will be the jointly optimal harvest.

Thus, under the modified ITQ system, it is no longer necessary for the fisheries authorities to set the TAC. This will generally be more efficiently set by the two associations themselves. We can go further and say that it doesn't matter what TAC the authorities set (as long as it exceeds the efficient one). Under the modified ITQ system, the TAC setting role of the fisheries authorities is basically redundant. Setting TACs is costly in terms of research and other things. Thus, at least to a certain extent, the modified ITQ system will save on these costs. It will certainly remove the need for the government to pay them.

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Appendix 1

Optimality conditions for the three marine resource users

Commercial fishermen

Commercial fishermen seek to solve the following maximization problem:

$$\underset{q,y}{Max} \int_0^{\infty} \prod(q, x) \cdot e^{-r \cdot t} dt$$

$$\text{Subject to:} \quad \dot{x} = G(x) - q - y.$$

$$q, y \geq 0$$

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The necessary conditions for a non-trivial solution ($q > 0$) to this problem (Pontryagin *et al.* 1962) involve:

$$\Pi_q = \lambda, \quad \text{(i)}$$

$$y = 0, \quad \text{(ii)}$$

$$\dot{\lambda} - r \cdot \lambda = -\Pi_x - \lambda \cdot G_x, \quad \text{(iii)}$$

$$\dot{x} = G(x) - q, \quad \text{(iv)}$$

where $\lambda > 0$ represents the shadow value of biomass to the commercial fishermen.

In equilibrium, $\dot{\lambda} = \dot{x} = 0$. Therefore, in equilibrium, the above conditions are reduced to:

$$G_x + \Pi_x / \Pi_q = r,$$

$$G(x) = q.$$

Note that the second of these conditions condition implies $y = 0$.

Recreational fishermen

Commercial fishermen seek to solve the maximization problem:

$$\underset{q,y}{Max} \int_0^\infty A(y, x) \cdot e^{-r \cdot t} dt$$

$$\text{Subject to:} \quad \dot{x} = G(x) - q - y.$$

$$q, y \geq 0$$

The necessary conditions for a non-trivial solution ($y > 0$) to this problem (Pontryagin *et al.* 1962) involve:

$$A_y = \lambda, \quad \text{(i)}$$

$$q = 0, \quad \text{(ii)}$$

$$\dot{\lambda} - r \cdot \lambda = -\Pi_x - \lambda \cdot G_x, \quad \text{(iii)}$$

$$\dot{x} = G(x) - q, \quad \text{(iv)}$$

where $\lambda > 0$ now represents the shadow value of biomass to the recreational fishermen.

In equilibrium, $\dot{\lambda} = \dot{x} = 0$. Therefore, in equilibrium, the above conditions are reduced to:

$$G_x + A_x / A_q = r,$$

$$G(x) = y.$$

Note that the second of these conditions condition implies $q = 0$.

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Conservationists

Conservationists seek commercial and recreational harvests that solve the following maximization problem:

$$\underset{q,y}{Max} \int_0^\infty B(x) \cdot e^{-r \cdot t} dt$$

$$\text{Subject to:} \quad \dot{x} = G(x) - q - y.$$

$$q,\ y \geq 0$$

The necessary conditions for a solution to this problem (Pontryagin *et al.* 1962) involve:

$$\lambda \geq 0,\ q \geq 0,\ q \cdot \lambda = 0, \quad \text{(i)}$$

$$\lambda \geq 0,\ y \geq 0,\ y \cdot \lambda = 0, \quad \text{(ii)}$$

$$\dot{\lambda} - r \cdot \lambda = -B_x - \lambda \cdot G_x, \quad \text{(iii)}$$

$$\dot{x} = G(x) - q - y, \quad \text{(iv)}$$

where $\lambda > 0$ now represents the shadow value of biomass to the conservationists.

In equilibrium, $\dot{\lambda} = \dot{x} = 0$. Therefore, in equilibrium, the above conditions are reduced to:

$$\lambda \cdot G_x + B_x = \lambda \cdot r,$$

$$G(x) = q + y.$$

Now, if either q or $y > 0$, $\lambda = 0$ according to (i) and (ii). So, in that case the equilibrium conditions are:

$$B_x(x) = 0,$$

$$G(x) = q + y.$$

If both q and y are zero, the equilibrium conditions obviously are:

$$G(x) = 0,$$

$$y = q = 0.$$

Note that in this case $B_x(x) \geq 0$, that is, the conservationists may prefer a larger biomass than the one nature can provide.

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Appendix 2

Desired equilibrium biomasses: a numerical example

Consider the following specification of the basic model in Section 1:

Biomass growth: $G(x) = \alpha \cdot x - \beta \cdot x^2$,

where x is biomass.

Benefit functions:

Commercial fishers: $p \cdot q - c \cdot q^2/x$,

where q is commercial harvest, p is landings price and c a cost parameter.

Recreational fishers: $\varepsilon \cdot y - \phi \cdot y^2/x$,

where y is recreational catch, ε benefits per unit of catch p and ϕ a cost parameter.

Conservationists: $\phi \cdot ln(x)$.

Parameter values are as follows:

Parameters	Values
α	2
β	1
p	1
c	2/3
ε	2
ϕ	3
φ	1

Applying the equilibrium conditions in Section 1, we find that the desired (optimal) equilibrium biomass values and harvests for the three parties are as follows:

		Optimal harvest	
	Optimal biomass	Commercial	Recreational
Commercial fishers	1.55	0.7	0
Recreational fishers	1.67	0	0.56
Conservationists	2.0	0	0

It may be added that under open access equilibrium, only the commercial fishers will prevail with sustainable biomass of 0.5 and harvest of 0.75.

Appendix 3

Operation of the ITQ system: commercial fishers

Consider I fishers. Let the benefit function of an arbitrary fisher i be:

$$\Pi(q(i), x; i),$$

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where $q(i)$ represents his harvest and x biomass.

The social objective is to maximize the present value of total benefits. In other words:

$$\underset{\forall q(i)}{Max} \int_0^{\infty} \sum_{i=1}^{I} \Pi(q(i), x; i) \cdot e^{-r \cdot t} dt$$

$$\text{Subject to:} \quad \dot{x} = G(x) - \sum_{i=1}^{I} q(i),$$

$$q(i) \geq 0, \ \forall i.$$

Necessary conditions to solve this problem include the conditions:

$$\Pi_{q(i)} = \lambda, \text{for all active fishers.} \tag{i}$$

$$\dot{\lambda} - r \cdot \lambda = -\sum_{i=1}^{I} \Pi_x - \lambda \cdot G_x. \tag{ii}$$

$$\dot{x} = G(x) - \sum_{i=1}^{I} q(i). \tag{iii}$$

The first condition requires all active fishers (the inactive ones have harvest of zero) to operate where marginal profits of harvest is equal to the shadow value of biomass. This is the requirement of allocative efficiency. The second and third conditions (combined with the appropriate initial and terminal conditions) jointly determine the optimal total harvest at each point of time, that is, the TAC, as $Q = \sum_{i=1}^{I} q(i)$ and the corresponding shadow value of biomass.

Now, consider the ITQ system discussed in Section 2. Under this system, any arbitrary fisher i holds a certain share $\alpha(i)$ in the TAC, Q. He can buy and sell quota shares (and quotas) at the market price s. He, thus, attempts to solve the following problem:

$$\underset{q(i),z(i)}{Max} \int_0^{\infty} (\Pi(q(i), x; i) - s \cdot z(i)) \cdot e^{-r \cdot t} dt$$

$$\text{Subject to:} \quad q(i) \leq \alpha(i) \cdot Q,$$

$$\dot{\alpha}(i) = z(i),$$

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

$$q(i) \geq 0.$$

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Necessary conditions to solve this problem are for all active fishers (Arnason 1990):

$$\sigma(i) = s. \tag{i′}$$

$$\dot{\sigma}(i) - r \cdot \sigma(i) = -\Pi_{q(i)} \cdot Q. \tag{ii′}$$

$$\dot{\alpha}(i) = z(i). \tag{iii′}$$

Conditions (i′) and (ii′) imply that all active fishers

$$\Pi_{q(i)} = \frac{r \cdot s - \dot{s}}{Q}, \forall i. \tag{A3.1}$$

It immediately follows that $\Pi_{q(i)} = \Pi_{q(j)}$ for all active fishers. This is equivalent to the requirement of allocative efficiency in the social optimal problem. This shows that the ITQ system generates allocative efficiency at each point of time. If, moreover, the TAC, that is, Q, is set correctly at each point of time, the fishery will also follow the optimal biomass path over time (Arnason 1990). Thus, provided the TAC is set correctly, this type of ITQ system will be fully efficient.

Appendix 4

Operation of the ITQ system: recreational fishers included

Now consider J recreational fishers in addition to the I commercial fishers discussed in Appendix 3. Let the benefit function of an arbitrary recreational fisher j be:

$$A(y(j), x; j)$$

where $y(i)$ represents his harvest and x biomass.

Assume that recreational fishers participate in the same ITQ system as the commercial fishers discussed in Appendix 3. Then any recreational fisher j will attempt to solve the following problem:

$$\underset{y(j)}{Max} \int_0^{\infty} (A(y(j), x; j) - s \cdot z(j)) \cdot e^{-r \cdot t} dt$$

$$\text{Subject to: } y(j) \leq \alpha(j) \cdot Q,$$

$$\dot{\alpha}(j) = z(j),$$

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

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$$y(j) \geq 0.$$

Necessary conditions to solve this problem imply (see Appendix 3):

$$A_{y(j)} = \frac{r \cdot s - \dot{s}}{Q}, \text{ all active } j.$$

Comparing this to Equation (A3.1) immediately shows that

$$\Pi_{q(i)} = A_{y(j)}, \text{ for all active fishers,}$$

which is allocative efficient.

Appendix 5

Socially optimal use of the resource

Taking all three groups; commercial fishers, recreational fishers and conservationists into account, the social problem is to:

$$\underset{q,y}{Max} \int_0^\infty (\Pi(q, x) + A(y, x) + B(x)) \cdot e^{-r \cdot t} dt$$

$$\text{Subject to:} \quad \dot{x} = G(x) - q - y,$$

$$q, y \geq 0.$$

In this formulation, all variables and functions are as defined in Appendix 1 above. Assuming in internal solution, necessary conditions include:

$$\Pi_q = \lambda, \tag{i}$$

$$A_q = \lambda, \tag{ii}$$

$$\dot{\lambda} - r \cdot \lambda = -\Pi_x - A_x - B_x - \lambda \cdot G_x, \tag{iii}$$

$$\dot{x} = G(x) - q - y. \tag{iv}$$

Thus, in optimal equilibrium, we find:

$$G_x + \frac{\Pi_x + A_x + B_x}{\Pi_q} = r,$$

$$\Pi_q = A_y,$$

$$G(x) = q + y.$$

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Appendix 6

Conservation under the ITQ system

In this appendix we only need to consider inter-sectoral quota trades, that is, trades between fishers and conservationists. We don't have to consider quota trades within the group of fishers as we already established in Appendices 3 and 4 that the ITQ system is efficient for allocating catches between fishers. We don't have to consider trades between conservationists either because for the conservationists the resource is a pure public good so there will be no incentive for them to trade amongst themselves.

Under the ITQ system, any individual conservationist will attempt to solve the following problem:

$$\underset{z(i)}{Max} \int_0^\infty [B(x;i) - v \cdot z(i)] \cdot e^{-rt} dt$$

$$\text{Subject to:} \quad \dot{\beta}(i) = z(i),$$

$$\dot{x} = G(x) - \left(1 - \sum_j^J \beta(j)\right) \cdot Q.$$

Where $B(x; i)$ is the benefit function of conservationist i, $z(i)$ his purchases of share quotas from fishers for conservation purposes and v the price of these quotas. $\beta(i)$ represents his accumulated quota shares, and J is the total number of conservationists. Q, as before, denotes the TAC.

For an internal solution, that is, a conservationist active in the quota market (but not holding all the quotas), the necessary conditions include the differential equations:

$$\dot{v} - r \cdot v = -\tau(i) \cdot Q,$$

$$\dot{\tau}(i) - r \cdot \tau(i) = -B_x(x;\, i) - \tau(i) \cdot G_x(x),$$

where $\tau(i)$ represents conservationist i's shadow value of the biomass.

It is useful to note that in full equilibrium ($\dot{x} = \dot{\beta}(i) = \dot{v} = 0$), the equilibrium price of conservation quota share is:

$$v = \frac{B_x(x;i)}{(r - G_x(x))} \cdot \frac{Q}{r}. \tag{A6.1}$$

Note that this price only depends on the stock of biomass (and the TAC) but is independent of the harvest rate. This is of course because, according to our assumptions, the conservationists' benefits depend on the stock of fish and not harvest as such.

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The conservationists acting as a group will try to solve the following problem:

$$\underset{\forall z(i)}{Max} \int_0^\infty \sum_{j=1}^{J} [B(x;\, j) - v \cdot z(j)] \cdot e^{-rt} dt,$$

subject to essentially the same constraints as the individual conservationists.

The necessary conditions include:

$$\dot{v} - r \cdot v = -\mu \cdot Q, \tag{A6.2}$$

$$\dot{\mu} - r \cdot \mu = -\sum_{j=1}^{J} B_x(x;\, j) - \mu \cdot G_x(x), \tag{A6.3}$$

where μ is the shadow value of biomass corresponding to the optimal solution for the conservationists as a group. Note that Equation (A6.3) involves the sum of the marginal benefits of biomass for all conservationists while the corresponding differential equation for the individual shadow price, that is, $\tau(i)$, is restricted to the marginal benefit of biomass to the individual himself. This, of course, is a mathematical representation of the underlying externality problem.

The equilibrium price of conservation quota share is:

$$v^* = \frac{\sum_{j=1}^{J} B_x(x;\, j)}{(r - G_x(x))} \cdot \frac{Q}{r}, \tag{A6.4}$$

where have used the '*' to indicate the conservation quota price for the jointly optimal solution optimal compared to the one generated by individual conservationists. Comparing Equation (A6.4) with Equation (A6.1) for the individual conservationist shows that the latter generally undervalues conservation quotas. Moreover, in most cases the undervaluation would be great. Thus, assuming identical conservationists the relations between the two prices in equilibrium would be:

$$v^* = J \cdot v,$$

where, it will be recalled, J is the total number of conservationists. This is sufficient to show that that the individual demand price for conservation quota shares would in general be less, and in most cases much less, than the socially optimal price (found by maximizing the total utility of conservationists).The reason again is the positive externality stemming from the public good nature of conservation.

Under the same ITQ system, individual fishers recreational and commercial attempt to solve the following maximization problem:

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$$\underset{z(i)}{Max} \int_0^{\infty} [\Pi(q(i), x) + v \cdot z(i)] \cdot e^{-r \cdot t} dt$$

$$\text{Subject to:} \quad q(i) \leq \alpha(i) \cdot Q$$

$$\dot{\alpha}(i) = -z(i),$$

$$\dot{x} = G(x) - \sum_i^I \alpha(i) \cdot Q.$$

Where $z(i)$ represent trades of quota-shares to conservationists. The necessary conditions for an interior solution include:

$$\dot{v} - r \cdot v = -\Pi_{q(i)} \cdot Q + \sigma(i) \cdot Q,$$

$$\dot{\sigma}(i) - r \cdot \sigma(i) = -\Pi_x - \sigma(i) \cdot G_x,$$

where $\sigma(i)$ represents fisher i's shadow value of the biomass.

In full equilibrium the price of a quota share traded with the conservationists is:

$$v = \left(\Pi_{q(i)} - \frac{\Pi_x}{r - G_x} \right) \cdot \frac{Q}{r}. \tag{A6.5}$$

The fishers acting as a group will try to solve the following joint maximization problem:

$$\underset{\forall z(i)}{Max} \int_0^{\infty} \sum_{t=1}^{I} [\Pi(q(i), x) + v \cdot z(i)] \cdot e^{-r \cdot t} dt,$$

subject to essentially the same constraints as the individual conservationists.

The necessary conditions for solving this problem include:

$$\dot{v} - r \cdot v = -\Pi_{q(i)} \cdot Q + \lambda \cdot Q, \tag{A6.6}$$

$$\dot{\lambda} - r \cdot \lambda = -\sum_{i=1}^{I} \Pi_x - \lambda \cdot G_x, \tag{A6.7}$$

where λ is the shadow value of biomass to the fishers as a whole. Comparing Equation (A6.7) to the corresponding differential equation for individual fishers, that is, $\sigma(i)$, reveals an externality effect similar to that of the conservationists. The jointly optimal solution involves the sum of the marginal benefits of biomass of all fishers, while the individual shadow price is restricted to the marginal benefit of biomass to the individual himself. This becomes even clearer when we look at the optimal conservation quota price in equilibrium:

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$$v^* = \left(\Pi_{q(i)} - \frac{\sum_i^I \Pi_x}{r - G_x} \right) \cdot \frac{Q}{r}, \tag{A6.8}$$

where we have used '*' to indicate the fishers' jointly optimal supply price of share quotas for conservation. Comparing Equations (A6.8) with (A6.5) for the individual fisher shows that the individual fisher generally overvalues conservation quotas. That is, he offers such quotas (and would demand them) at too high a price compared to the true social value. In other words, individual supply curves of quota shares for conservation would be higher (the offer price higher) than would be optimal for the fishers as a group. The reason, as before is the positive stock-externality of such sales. As individual fishers only reap a part (usually a small fraction) of the stock benefits of conservation, they are less willing than overall optimality would suggest to sell quotas for such a purpose.

Now, consider what would happen under the ITQ system, when fishers and conservationists acting as two separate groups maximize their benefits. In that case Equations (A6.2) and (A6.3), and (A6.6) and (A6.7) apply. Eliminating the conservation quota share price, v, and the two shadow values of biomass, τ and λ from this system and writing $\sum_{i=1}^{I} \Pi_x(q, x; i) \equiv \Pi_x$ and $\sum_{j=1}^{J} B(x; j) \equiv B_x$ yields after some rearranging:

$$\dot{\Pi}_q - r\Pi_q = -\Pi_x - B_x - \Pi_q \cdot G_x \tag{A6.9}$$

Expression (A6.9) defines a function in x and q only. At the same time, the biomass growth constraint:

$$\dot{x} = G(x) - q$$

must hold. These two equations define the path of harvests, q, and biomass over time. Notice that they are identical to the socially optimal solution defined by expressions (i)-(iv) in Appendix 5. This shows that under these conditions, that is, when the conservationists and the fishers act as groups, the ITQ system leads to overall economic efficiency.

It is also worth noting that these equations do not depend on TAC decisions by an outside agency. Thus, under the conditions specified, ITQ trades will not only lead to the socially optimal allocation of harvests and harvest shares but the optimal TAC as well.

Finally, the above leads to interesting relationship between fishing and conservation quota prices. Expressions (A6.2) and (A6.6) imply:

$$\lambda + \mu = \Pi_q, \forall t, \tag{A6.10}$$

where Π_q is the marginal benefits of harvest common to all active fishers.

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Combining Equations (A3.1) and (A6.6) yields, after a little rearranging, a useful relationship between the price of a fishing quota, that is, s (see Appendix 3), and the price of a conservation quota, that is, v:

$$\frac{\dot{v} - r \cdot v}{Q} = \frac{\dot{s} - r \cdot s}{Q} + \lambda.$$

So the difference between the two prices, say, $\Delta = s - v$, evolves as:

$$\dot{\Delta} = r \cdot \Delta - \lambda \cdot Q.$$

And in equilibrium

$$s = v + \frac{\lambda \cdot Q}{r}.$$

Now, λ is the shadow value of biomass to the fishers. This must be non-negative and positive if fishing is at all profitable. In that case, it follows immediately that in equilibrium $s \geq v$, with the inequality sign applying if fishing is profitable (takes place). In that case, the price of fishing quota must be greater than the price of conservation quota. It is, moreover, not difficult to show that if $\Delta > 0$ in equilibrium and the equilibrium will ultimately be reached, then $\Delta > 0$ along the optimal dynamic path as well.

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