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Conflicting uses of marine resources:
Can ITQ's promote an efficient solution?

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Conflicting uses of marine resources: Can ITQ's promote an efficient solution?

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Abstract

This paper examines the problem of conflicting use of marine resources by (i) commercial fishers, (ii) recreational fishers and (iii) conservationists. It is shown that the standard system of individual transferable quotas (ITQs) is, without any modification, capable of allocating resource use between the first two parties in the socially optimal manner both collectively and individually. 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, i.e. all fishers, and conservationists. The fundamental reason is that quota trades between individual fishers and conservationists are inevitably accompanied by external effects on both other fishers and other conservationists. As a result decentralized decision making doesn't work. In a fundamental sense, quotas for conservation purposes and for extraction purposes constitute two different goods. It follows that a socially optimal market allocation of these two goods requires two quota prices instead of the one in the standard ITQ system. Thus, to achieve efficiency, the ITQ system has to be extended to take account of both goods. It is shown in the paper, that if both fishers and conservationists can organize themselves as groups, conservation quota trades between the two groups can in principle lead to fully efficient allocation. An interesting implication of this modified ITQ system is that the need to a fishing authority to set the total allowable catch (TACs) disappears.

Keywords: Conflicting use of marine resources, ITQs, conservation quotas, fishing and conservation conflicts, commercial and recreational fishing conflicts.

0. Introduction

The oceans can be used for many different purposes. Minerals, fish and vegetation may be extracted from the oceans. By-products of human production and consumption may be dumped into the oceans. The oceans may be used for travel and transportation. Ocean resources may be used directly for consumption of various kinds including recreation and conservation enjoyment.

Due to the wide range of usage types, classification of ocean use is not easy. It may help, however to think of three broad categories; (i) *extractive use* of which ocean fishing and mining are examples, (ii) *insertive use* of which pollution is the prime example and (iii) *passive use* which covers a very wide range of activities from travel on the surface to ocean to conservation demand of various kinds (option demand, bequest demand, existence demand)[1]. It should be noted that actual ocean use rarely belongs exclusively to one of these categories. Thus, for instance, fishing and mining, typical ocean extractive activities, usually also insert pollutants into the ocean. Obviously travel and recreational use of the oceans also generally involves insertive use as well and sometimes even extractive use.

Many of these different uses of the oceans conflict (i.e, compete; are rival) in the sense that they alter available benefits to other uses. Thus, obviously extractive and insertive uses of the oceans may interfere with conservation enjoyment. Many insertive uses of the ocean may affect biological productivity and thus reduce extractive possibilities. Various kinds of extractive uses also interfere with each other. Fishing by individual companies generally reduces the availability of fish to other companies and may, in extreme cases, adversely affect the long term renewability of the fish stocks. Ocean mining may negatively affect the opportunities for fishing and so forth.

This paper deals with the situation where a fish stock, or more generally a renewable natural resource, has different uses. More precisely we consider the situation where it has three different uses: (i) for generating commercial harvests, (ii) for generating recreational harvests and (iii) for generating conservation utility on the other. Under a complete system of property rights and smoothly functioning markets, market trades will normally bring about the a Pareto-efficient solution. However, in a situation of limited property rights, not to mention a common property arrangement, the outcome will generally not be anywhere close to being Pareto-efficient.

In recent years tradable quantity rights, often referred to as individual transferable quotas or 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 indeed capable of maximizing economic rents from a previously common property fishery. This theoretical result has received empirical support from the experience with a number of ITQ-managed fisheries around the world (Shotton, 2000).

Similar approaches have been adopted is other natural resource uses, notably the tradable CO_2 emission quotas on the North American east coast. Also here, the

1 For the various passive use values of the environment see e.g. Hanley et al. 1997.

empirical evidence supports the theoretical prediction that such instruments enhance efficiency in the use of the underlying natural resources (Schmalensee et. al. 1998 and Stavins 1998).

The application of ITQs to fisheries is designed to promote allocative efficiency in the use of the total allowable catch amongst commercial users of the resource. What has not been explored is to what extent the ITQ instrument can also serves to promote allocative efficiency when the resource in question also has an alternative use for direct consumption in the form of recreational fishing or/and conservation. This represents a serious gap in our understanding because there are indications that these other uses are often of high valuable compared to the commercial extraction. Consequently, errors in the allocation of use can lead to a loss in social welfare.

This paper constitutes an attempt to study the feasibility of employing ITQs to bring about the social optimal balance between resource conservation and extraction. The strategy of the paper 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 is a reason for further exploration long these lines.

As will become clearer as the paper progresses, the question of efficient allocation of a fish resource to conflicting uses revolves very much around three closely related concepts: (i) *property rights*, (ii) *externalities* and (iii) *public goods*. It has long since been established (Gordon 1954) that commercial fishers, by extracting from a common stock of fish, impose negative externalities on each other. These externalities, as indeed all externalities, are caused by imperfect or missing property rights. It follows that they can be eliminated[2] by the introduction of the appropriate property rights. ITQs are examples of property rights for this purpose. Recreational fishing is extractive in the same way as commercial fishing leading to the same externality problems which, it will be shown in this paper, can be solved in the same way. When it comes to conservation demand, however, the situation is somewhat different. Conservation measures taken by individual conservationists result in positive externalities for other conservationists as well as fishers (who will now enjoy larger stocks). The reason is the same as before, namely lack of property rights. The fish stock is a common good and any addition to it via protection, stock enhancement and so on, benefits all users. In the case of conservation, which represents a non-extractive use of the resource, the stock is basically a public good. The fundamental insight is that due to this public good nature of conservation benefits, individual property rights and decentralization on the basis of trades will not solve the allocation problem. In the case of extractive use the benefits of extractions befall the extractor. Hence, provided there are property rights in extraction (and the negative externalities are corrected for by TAC), individual trades will solve the allocation problem. In the case of conservation use, the benefits of conservation befall all conservationists. The good in question is fundamentally a public good. Private property rights cannot be defined and imposed. Hence individual trades can never lead to an efficient allocation

[2] Actually the externalities as human interactions do not disappear. They are merely turned into what economics call pecuniary externalities which leads to the appropriate economic adjustment to their existence.

between the conservationists. It is only by operating as a group or a club that the conservationists can approach a reasonable level of conservation.

The paper begins by characterising the nature of the conflict regarding the use of the fish resource by the three parties. This appears as a disagreement about total harvest rates, who should harvest and optimal stock levels. This is followed, in section 2, by explaining how the ITQ system can resolve this type of resource use conflict amongst commercial fishers. In section 3, it is shown that the same ITQ system can similarly resolve the same conflict amongst recreational fishers and, perhaps more importantly, reconcile the conflicting interests of commercial and recreational fishers in the socially optimal manner. Section 4 explores to what extent the ITQ system can serve the same 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 of conservation, the usual ITQ system will not perform this function well, although it would probably constitute an improvement. However, under a modified ITQ system where 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. The final section, section 5, summarizes the results of the paper and discusses the main implications.

1. Describing the basic situation

Let us begin by modelling the basic situation and explain the nature of the use conflict. Consider a fish stock or, for that matter, some other living marine resource whose dynamics are given by:

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

where x represents the stock biomass and z the aggregate harvest. The function $G(x)$ is the biomass growth function exhibiting the usual properties (see e.g. Clark, 1975) namely that $G_{xx}(x) < 0$ and that $\exists\ x_1$ and x_2 such that $0 \leq x_1 \leq x_2$ and $G(x_1) = G(x_2) = 0$.

Consider now a ***fishing industry*** with an instantaneous benefit (profit) function

(2) $\Pi(q,x),$

were q represents harvest. The function $\Pi(q,x)$ is assumed to be monotonously increasing in biomass, x, and concave in both arguments. To make the situation interesting, we assume that there exists a biomass level such that the benefit function is positive and increasing in the harvest level, q up to a certain point. The fishing industry consists, of course, of a number of different fishers.

Next consider a ***recreational fishery***. For our purposes it is immaterial whether this is a commercial recreational fishery, where specialized firms offer fishing recreation to customers, or a pure recreational activity, where individuals simply fish for their own enjoyment, or a combination of both. Let the benefit function from this fishery be:

(3) $A(y,x)$,

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 instantaneous benefits are increasing in the biomass of the fish stock, at least up to a point. More precisely

(4) $B(x)$.

It may be noted that according to the above, the commercial and recreational fisheries constitute extractive use of the fish stock (or more generally any marine resource), while the conservation use is passive.[3] It is also very important to 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.

Now each of these three groups, the commercial fishers, the recreational fishers and the conservations, consists of a number of individual members. The preferred harvests and stock size of the individual members in each group are normally not identical. 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 discussed in the introduction. Thus each fisher would like all other fishers to completely refrain from harvesting. For the time being we assume that each group has somehow solved their internal contradictions — presumably by adopting a policy that maximizes the total benefits to the group — and acts as one unit.

We assume that each party seeks to maximize the present value of its flow of benefits over time. For simplicity we assume, moreover, that all have the same rate of discount, r.[4]

Now, it is easy to demonstrate that the desired stock size of the parties, 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 their respective maximization problems. This is done in Appendix 1. In a nontrivial (positive biomass) equilibrium, the desired harvesting values and biomass, x, for the three parties acting as groups are as follows (see Appendix 1):

***Commercial fishers*:**

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3 It is conceivable that active conservation use also impacts on the fish stocks (e.g. by observing the fish. The basic approach of this paper is easily generalized to incorporate this..

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

(5)
$$G_x + \Pi_x/\Pi_q = r,$$
$$G(x) = q$$

Since according to the latter equation above, all the harvest is commercial, the commercial fishers want the recreational harvest to be y=0.

Recreational fishers

$$G_x + A_x/A_y = r,$$
$$G(x) = y.$$

Since according to the latter equation above, all the harvest is recreational, the recreational fishers want the commercial harvest to be q=0

Conservationists[5]

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. In that case their optimality conditions are:

(6)
$$G(x) = 0$$
$$y=q=0$$

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.

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

(6')
$$B_x(x^*)=0$$
$$G(x^*) = z=q+y,$$

where $x^*<x_2$ denotes the desired biomass by the conservationists. So, in this case the conservationists want a certain culling of the biomass. Note, however, that, at least in this simple representation, they don't care whether the culling is by recreational or commercial fishermen.

Expressions (5) for the commercial fishers are well know in the fisheries economics literature as the equilibrium conditions for the optimal fishery (Clark and Munro, 1975, Arnason 1990). The term Π_x/Π_q which will play some role below is referred to as the marginal stock effect by Clark and Munro (1975). Given profit maximization, the marginal stock effect is nonnegative and its effect is to increase the equilibrium biomass compared to what would otherwise be the case.

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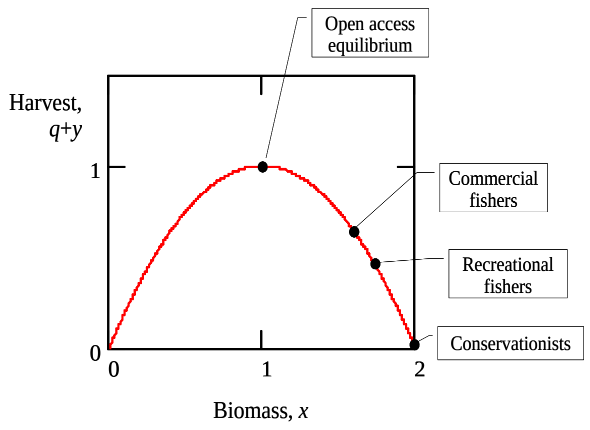
5 This assumes that the conservationists do not want as large a biomass as possible. If that were the case, the conditions would change to: $G_x(x^*)=0$ and $z=y+q=0$.

The optimal equilibrium conditions for the recreational fishers are formally identical to 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 would generally be different to that of the commercial fishers.

The content of equations (6) and (6') are more novel and warrant some discussion. First, note that the equation systems 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, at a point where the marginal benefits of biomass to the conservationists is zero. Where that happens, if at all, 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 in which case, the conservationists would like to see not harvesting but stock enhancement. It is also possible that the conservationists would like to see the biomass level at zero indicating that they regard the species as a pest.

It is obvious that only very coincidentally would these three sets of optimality conditions 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. With this the commercial and recreational fishers would only agree if neither of them would gain benefits from harvesting at that biomass level, i.e. extraction would not yield any benefits even at this high biomass level. If commercial fishermen can extract benefits from the fishery, they would generally not want any harvest by recreational fishers and vice versa. An example of these conflicting desires is worked out in Appendix 2. The outcome is in terms of sustainable or equilibrium biomass is illustrated in Figure 1.

Figure 1
Desired biomass and harvest



2. Individual transferable quotas, ITQs, and commercial fishing

Individual transferable quotas 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 and between 10 and 15% of the global ocean catch is currently 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 variant, IQs, are by far the most widely used property rights instruments in the world's fisheries today.

Consider the following ITQ system: There is a total allowable catch, TAC, which applies at each point of time. Individual fishers hold permanent rights to a certain fraction of the TAC. These rights, or quota shares, are perfect property rights, i.e. they are fully exclusive, secure, permanent and tradable. It is important to realize, however, that they are fairly weak property rights in the resource itself, namely the fish stocks and their ocean environment (Arnason 2000).

This ITQ system works by eliminating (or, more precisely, neutralizing) the stock externality which is the predominant cause of the fisheries problem. It does so in two ways: First, by setting the TAC the total extraction level is fixed.[6] Therefore, the evolution of the stock over time becomes exogenous to the harvesting decisions of the fishers.[7] Second, due to the individual quota constraint, no fisher can impose externalities on the other fishers, at least not above what his quota permits. A fisher cannot increase his share of the TAC unless other fishers agree to give him some of their quota rights. Thus, in a fundamental way the stock externality, the most damaging externality in the fishery is eliminated (Arnason, 1990). Note, that the externality disappears by virtue of the property rights comprised by the ITQs. This illustrates the basic theorem discussed in the Introduction that externalities always arise as a consequence of missing or imperfect property rights. It immediately follows that if the property rights value of the ITQs is somehow reduced, e.g. by imperfect enforcement, the stock-externality will generally reappear.

ITQs are property rights in harvest. Provided the ITQs are fully tradable, it follows that the allocation of stock use, i.e. harvests, will be economically efficient (Arnason, 1990). Only the most efficient firms will harvest the TAC. The reason for this is simple. If a less efficient firm holds an ITQ, it will find it profitable to sell or rent a part of this ITQ to a more efficient fishing firm. This applies to all firms at all times. Thus, as a result, at each point of time, it is only the most efficient firms that are engaged in harvesting. Moreover, the allocation of harvests between active firm will be economically efficient. For that to be the case they must all be operating at a point where they generate the same marginal benefits. This is precisely what happens under the ITQ system. Again the reason is profit maximizing trading. If one firm is operating at a lower marginal benefit than another, then they will both profit from transferring a part of the first firm's ITQs to the second. Hence, in a trading equilibrium, the marginal benefits of quota use will be equal. This common marginal benefit is also the equilibrium price at which quotas are exchanged.

Thus, we see that under this ITQ system, the right number of the most efficient firms operating at the optimal level will do the harvesting. A very important thing to note is that this allocative efficiency happens in a totally decentralized manner. It is brought about by individual fishers trying to maximize their own benefits. This they can do by reallocating quotas amongst themselves by trading. These trades, for the usual economic reason, are in the direction of more efficient allocation. So, the allocative efficiency of the ITQ system depends critically on the tradability of the

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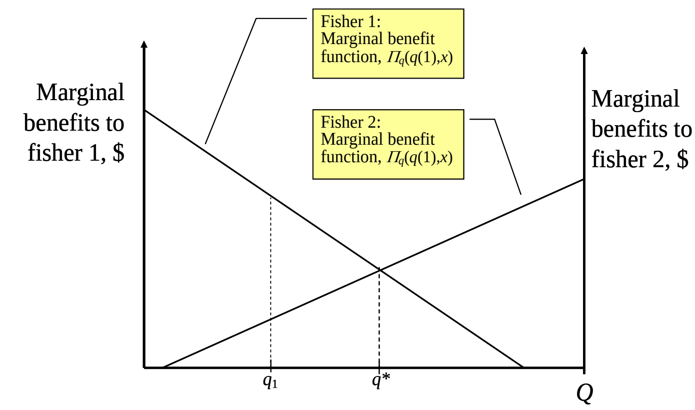
6 This obviously assumes that individual quota constraints are enforced.

7 It has been shown by Arnason (1990) that it is never optimal for commercial fishers to leave quopta unused.

quotas. However, interestingly, it does not depend on how the quota-shares are initially allocated. Irrespective of the initial allocation of quota shares, profit maximizing trading will always move them to the most efficient fishing firms.

We can illustrate this basic allocative efficiency of the ITQ system with a simple diagrammatic device. Consider the allocation of harvests between any two fishers. For analytical purposes, we do not have to consider all fishers at the same time because one of them, fisher 2, say, could represent all the remaining fishers. Having determined the allocation of harvests between fisher 1 and the rest, we could move on to the first fisher in the remaining group and so on. Now, each fisher receives certain marginal benefits from harvesting. 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 the marginal benefits to fisher 2 on the right-hand vertical axis. The total harvest to be allocated, i.e. the *TAC*, is measured along the horizontal axis between the two vertical axes and we refer to it as *Q*. 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.

Figure 2
Optimal allocation of resource use (fishing)



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, i.e. 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 the two fishers will converge, irrespective of the initial allocation 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**. Thus, we can use this diagrammatic device to see that the ITQ system results in efficient allocation of the total allowable catch (TAC) between fishers.

At the optimal allocation point, *q**, the two marginal benefit curves are equal at the value *s* in the diagram. In quota market equilibrium this will be the equilibrium quota price. It may be interesting to note 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, e.g. 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

Thus, for any TAC set, the fishery will operate as efficiently as possible. 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 basically has to be set in such a way that the fishery follows the optimal path toward equilibrium. It is straight-forward to define this path analytically. Due to the lack of necessary information, to find it in practice is a different proposition. Provided markets work, it can be shown (Arnason 1990) that the optimal TAC at each point of time is the one that maximizes the overall quota values. Thus the problem of finding the right TAC is reduced to selecting the one that maximizes the value of quota shares. Moreover it turns out in most empirical cases that this value function is quite flat around its maximum level. Thus, it generally, is not of any great consequence to make relatively small errors in setting the TAC provided it is in the neighbourhood of the optimal level and the errors are not one-sided.

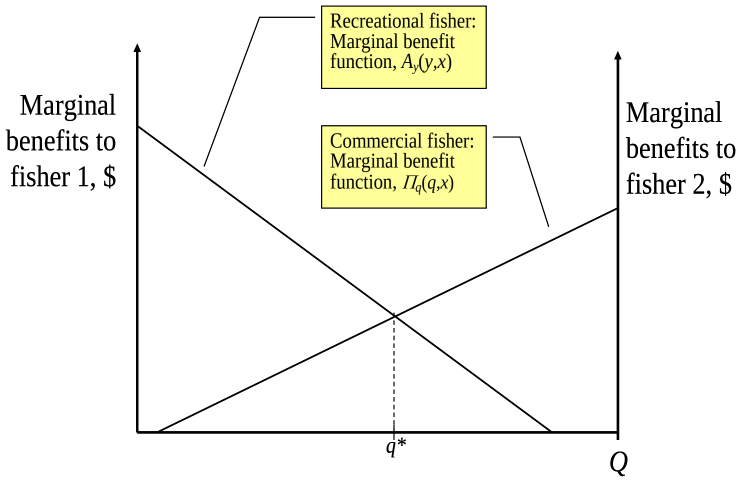
Typically, in most countries that employ ITQs, the TACs are set by the fisheries authorities. However, there is no reason for that to be so. Any agency that can locate the maximum of the share quota value function is capable of setting the optimal TAC. In fact, due to their overriding incentive to maximize their wealth and their intimate knowledge of the fishery it appears that the industry, acting as a whole, is probably in the best position to set TAC itself.

3. Reconciling Commercial and Recreational Fishing under ITQs

We have seen how ITQs can harmonize conflicting demands for commercial harvests from fish stocks. What about other extraction demands from, say, recreational fishermen? The answer is that these demands can be completely reconciled with commercial fishing demands within the framework of the ITQ system. The reason is simple. Recreational demands for harvests is analytically identical to the 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 the 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. At the same time, for any given TAC, less beneficial recreational fishing should give way to make room for the commercial fishing.

Under the ITQ system, this is exactly what will be the outcome. If a recreational fisher gets more benefits from fishing than a commercial fisher, it will in the interest of both to trade some commercial quotas to the recreational fisher and vice versa. This is illustrated in Figure 3. In this figure fisher 1 is a recreational fisher and fisher 2 the remaining group of all fishers, commercial and recreational. The optimal allocation of harvests is q^* and as argued in section 2, this is going to be brought about by quota trades. At this optimal point the marginal benefits to both the recreational fisher and the commercial fishers are the same and equal to the market price for quotas, s. This market price, however, would normally be different than if only the commercial fishers were included in the quota system. Note, moreover, that as before, it doesn't matter for allocative efficiency how the quotas are initially allocated. 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 could easily be eliminated from active participation in the fishery.

Figure 3
Commecial and recreational fisheries



This discussion, however, ignores the setting of the optimal TAC level. With the addition of the recreational sector, the optimal TAC, i.e. the one that maximizes the value of the total fishery (recreational and commercial) would generally be changed. More specifically, with recreational fishing included, the optimal equilibrium conditions for the fishery will be defined by the conditions:

$$G_x + (\Pi_x + A_x)/\Pi_q = r,$$

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

$$\Pi_q = A_y.$$

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 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, (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 the both the optimal biomass and TAC will be altered. If both industries should operate, the combined optimal biomass will be some average of the ones the parties 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 maximize the total value of all quota shares recreational and commercial.

4. Conservation and fisheries

Now that we have seen that we can essentially combine recreational fisheries with the fishing industry and that ITQs solves the efficiency problem for both, let us turn our attention to the conflicting interests of the fishery and fish conservation. For this purpose, let the benefit function $\Pi(q,x)$ represent the combined benefits of commecial and recreational fishers.

Social optimum

The social problem is to select the extraction profile, possibly identically zero, that maximizes the present value of fishing and conservation benefits from the resource. More precisely

$$\underset{\{q\}}{Max} \int_0^\infty (\Pi(q,x) + B(x))\cdot exp(-rt)dt$$

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

In what follows this problem will be referred to as the extraction-conservation problem.

Necessary conditions for solving the extraction-conservation problem lead to the following set of differential equations:

$$\text{(8)} \quad \begin{aligned} &\dot{\Pi}_q - r\cdot\Pi_q = -\Pi_x - B_x - \Pi_q G_x, \\ &\dot{x} = G(x) - q \end{aligned}$$

whose equilibrium solution is given by

$$\text{(9)} \quad \begin{aligned} &G_x + (\Pi_x + B_x)/\Pi_q = r, \\ &G(x) = q. \end{aligned}$$

It is interesting to compare (9) with the optimal equilibrium conditions for the fishery as given by (5). The only difference is that the socially optimal marginal stock effect has now been augmented by the term B_x that reflects the marginal benefits of the resource stock to the conservation lobby. Provided B_x is positive (which would normally be the case for true conservationists), the marginal stock effect is now larger than before implying a larger optimal equilibrium stock level than the fishing industry would prefer. In terms of Figure 1, the socially optimal equilibrium stock would normally be between the one desired by fishers and the one desired by the conservationists with the exact point depending on the relative size of the benefits to each party.[8]

An ITQ system

The above analysis shows that conflicting demand for the services of a natural resource by fishers and conservationists will generally not be resolved in a socially satisfactory manner unless there exist mechanisms that can somehow weigh and compare the interests of the parties involved. We have already seen that the ITQ system can do this for the conflicting interests of commercial and recreational fishers. We now consider to what extent the ITQ system can perform the same harmonizing role for fishers and conservationists.

Consider the usual proportional ITQ system, i.e. one where the quota rights (ITQs) are permanent shares in whatever total allowable catch (TAC) is set by the managing authority and freely transferable. To this system let us add the provision that the quota shares can be traded between the conservationists and the fishers. While the fishers buy quota shares for fisheries purposes, the conservationists buy them to prevent them to be used for fishing.

A formal analysis of the effects of this system is somewhat complicated and lengthy and has therefore been relegated to Appendix 4. The crucial result of that analysis is that the usual decentralized ITQ system will not bring about the socially optimal allocation of resource use. In other words, it will not result in the socially optimal biomass and harvest paths specified in equations (8).

The fundamental reasons for this outcome, although complicated to derive formally, are not difficult to understand. Within the ITQ system, the conservationists buy quotas to prevent them being fished. Thus, the effective TAC is altered and the stock-externality is reintroduced into the system. It is, however, not reintroduced completely because fishers holding ITQ-shares still control their individual quotas and can fish them with impunity. It is only that the path of the biomass, which under the usual ITQ system restricted to fishers is exogenous, has now by virtue of the conservationists buying (and possibly selling) quota shares become endogenous again. So, in one sentence, the conservation demand for ITQ-shares imposes an externality (a positive one if they are buying and a negative one if they are selling) on the fishers.

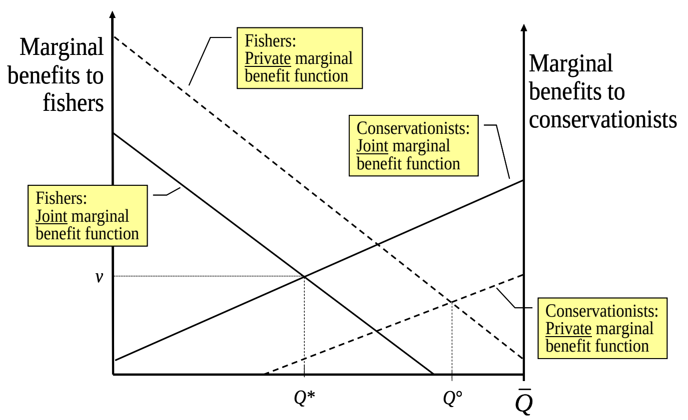
This, however, is not all. The stock of fish is a common good to all conservationists. So, if one conservationist buys quota for conservation he is not only benefiting himself, he is generating benefits for all other conservationists (in addition to the benefits to the fishers discussed above). This is like the fisheries common pool

8 There are, of course, special cases where desires of one of the parties would rule. One is the case where the conservationists are happy with the biomass generated by the fishers. This characterized by the condition that $B_x(\hat{x})=0$ where $\hat{x}$ represents the desired equilibrium biomass level of the fishers. The other is where the marginal benefits of stocks to the conservationists at the virgin stock equilibrium exceed the benefits from harvesting at that level. Formally the condition is $B_x(x_2) \geq \Pi_q(0, x_2)(r - G_x(x_2))$, where x_2 is the virgins tock equilibrium.

problem in reverse. When one conservationist takes conservative action he is imposing an externality, in this case a positive one, on all the other conservationists. As a result, each conservationist tends to do little conservation action compared to what 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 fisher's ITQs in Figures 2 and 3. In Figure 4 the TAC has been set at $\bar{Q}$. 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 $\bar{Q}$. Note that effective TAC, i.e. the part of $\bar{Q}$ that is actually going to be fished, is represented by the fishers share and the un-fished part by the conservationists' share. It is important to be clear that any point along the horizontal axis is now the effective TAC, i.e. the actual total catch. It is no longer the allocation of total catch between the parties as in Figures 2 and 3 above. The horizontal axis still represents an allocation, i.e. the allocation of resource use between fishers and conservationists. This particular allocation, however, is equivalent to setting the effective TAC (in contrast to the official TAC). In what follows we will for convenience simply refer to the effective TAC as the quota and denote it by *Q*. The fishers' marginal benefits of *Q* are measured along the left-hand vertical axis and the conservationists' marginal benefits of the *Q* along the right-hand vertical axis.

Figure 4
Fishing vs. Conservation Allocation



In Figure 4, the fishers' joint marginal benefit curve of *Q*, i.e. the one that results from solving their joint maximization problem, is drawn as the downward sloping curve. The conservationists, joint marginal benefit curve, i.e. the one that maximizes their total benefits, is drawn as the positively sloped curve. Seen as benefits, this curve is measured from right to left, i.e. from $\bar{Q}$. So it is really marginal benefits of increased conservation quota. Alternatively, measured from left to right, this curve can be interpreted as their marginal cost curve of increased catch. Indeed, this is the way this kind of a diagram is usually interpreted in the environmental economics literature (see e.g. Hanley et al 1997). It is useful to note that the two margin al benefit curve can also been seen as supply and demand curves. They represent parties the desired quota, *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 $\bar{Q}$ 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 joint optimal quota is at 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 the ITQ system. In deciding on quota trades, individual fishers and conservationists will only think of their own private benefits and costs and not take account of the external benefits of increased conservation quotas into account. In other words, the marginal benefit curves of fishers and conservationists will underestimate the true benefits. The private marginal benefit curve of fishers (aggregated over the whole industry) will be higher and the private marginal benefit curve of the conservationists (aggregated over all conservationists) will be lower than the joint ones as illustrated in Figure 4. As a result, fishing will take place at Q^o instead of Q^*. So, there is less conservation than would be socially optimal. Indeed, depending on the conservationists' private demands there might not be any conservation. The price of conservation quotas can be either higher or lower than the socially optimal one.

So, the usual decentralized 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. Note, however, that the ITQ system can only represent a social improvement compared to not allowing conservationists to participate in the ITQ system. 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 decentralized 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 bargaining equilibrium, the parties will agree on the harvesting solution that maximizes their joint benefits. Under those circumstances it is shown in Appendix 4 that the actual harvesting quota and biomass paths will be described by exactly the same set of differential equations as the optimal solution (8) above.

So, in this form of centralized ITQ system, where both parties, the fishers and the conservationists, internalize their respective conservation externalities by acting as groups, ITQ trades will indeed lead to the socially optimal harvesting quotas at each point of time. Due to the potential importance of this result we express it formally as proposition 1.

Proposition 1
Under the conditions specified (i.e. an ITQ system where fishers as a group, trade conservation quotas with conservationists as a group), and in a bargaining equilibrium the extraction-conservation problem will be solved.

It is important to realize that the result in Proposition 1 holds not only in equilibrium but also along the adjustment paths (of biomass and quota share holdings). Also, although not demonstrated here, the basic result also holds for variants of the ITQ system e.g. where the quotas are not permanent (cannot be accumulated), quantity quotas rather than share quotas and so on.

Apart from the basic result expressed in Proposition 1, the analysis suggests a number of interesting results: First, the TAC, i.e. Q, is basically irrelevant. Provided it is sufficiently large to allow the harvest agreed on, it can be anything.[9] The basic reason is that trades between the conservationists and the fishers actually determine the effective TAC as $\alpha \cdot Q$. Therefore, the actual TAC is irrelevant.

Second, it follows from the above that the usual function of the fisheries authorities of setting the TAC is no longer necessary. This is superseded by the trades between fishers and conservationists. This should actually not be surprising. In the pure fisheries case, i.e. no conservation interest, it is easy to show that the fishing industry acting as one would set the optimal TAC.

Third, 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 (see below)

Fourth, equations (11.1) and (13.1) imply an interesting relationship between the two parties' evaluation of the shadow value of biomass. Namely,

(14) $\lambda \cdot + \tau = \Pi_q, \forall t.$

This means that along the optimal utilization path of the marine resource utilization, the marginal benefits of harvest to fishers must be equal to the sum of the shadow value of the resource to fishers, λ, and the shadow value of the resources to conservationists, τ. Moreover, this relationship must hold at all times. Now, if the shadow value of the resource to the conservationists is positive, i.e. they actually value the resources (as we have assumed), this immediately implies that for any given biomass the harvest would be less than it otherwise would have been. Of course, in the case where the conservationists actually get disutility from the biomass — the biomass is a pest of some sort — τ becomes negative and the fishers should harvest more than they would do otherwise.

Fifth, under the above arrangement, there are basically two different types of quota shares, conservation quotas and fishing quotas. The conservation quotas are the ones that trade between fishers and conservationists and are subject to bilateral negotiation. The 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. In Appendix 4, 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 stocks. Therefore, 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

[9] In fact, if it is not large enough, all that needs to be done is to abolish the constraint that the sum of quota-shares have to equal unity.

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.

5. 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 this is derived assuming perfect and costless enforcement of the ITQ system. Obviously, costly and imperfect enforcement might imply certain modifications of the result. I 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 external effects associated with the conservation activity. First, allowing purchases of quota shares for conservation purposes within the ITQ system reintroduces a part of the stock-externality, which the ITQ system was designed to neutralize. Second, conservation is inherently a public good. One conservationist's purchase of fishing quota for conservation purposes benefits all conservationists. It, thus, generates a positive externality.[10] 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 less than would be socially optimal. Consequently, under decentralized quota trades, the level of fishing will be higher and that of conservation lower than would be socially optimal.

So, the usual (decentralized) ITQ system will not work to allocate resource use optimally between the conflicting demands of fishers and conservationists. It is important, however, to realize 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. This then would represent a social improvement compared to not including conservationists in the ITQ system at all.

It turns out, however, that a certain modification of the ITQ system will lead to a fully efficient allocation of resource use between fishers and conservationists. The modification is briefly that the usual (decentralized) ITQ system applies within the group of fishers (extractors), but trades between fishers and conservationists are centralized in the sense that they can only be conducted between the two parties as groups.[11] It is shown in the paper that under this system the allocation of resource use

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

[11] 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.

will be identical to the optimal, at least in bargaining equilibrium. Moreover, this result applies both in stock equilibrium and along dynamic adjustment paths. The reason for this is fairly obvious. By acting as a group, fishers internalize the stock-externality of setting quotas aside for conservation purposes. Similarly, by acting as a group, the conservationists internalize the conservation externality. In other words, by acting as groups both parties effectively turn the public good attribute of conservation into a club good. 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 realize, however, that this is a theoretical result. To actually set up or implement the modified ITQ system in practice is a fairly complicated undertaking. First, the two groups or associations must be established. This is obviously not straight forward. Second, the two associations must be organized in a way that generates incentives to maximize the total benefits of their members. This, as is well known, is a major problem in organizational 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, i.e. the real total allowable catch. 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 one.

Thus, under the modified ITQ system, it is no longer necessary for the fisheries authority 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 effective one). Under the modified ITQ system, the TAC setting role of the 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:

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

Subject to: $\dot{x} = G(x) - q - y$.
$q, y \geq 0$

The necessary conditions for a nontrivial solution (q>0)to this problem (Pontryagin et al 1962) involve:

(i) $\Pi_q = \lambda$,

(ii) $y = 0$,

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

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

where λ>0 represents the shadow value of biomass to the commercial fishermen

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

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

$G(x) = q$.

Recreational fishermen

Commercial fishermen seek to solve the maximization problem:

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

Subject to: $\dot{x} = G(x) - q - y$.
$q, y \geq 0$

The necessary conditions for a nontrivial solution (y>0)to this problem (Pontryagin et al 1962) involve:

(i) $A_q = \lambda$,

(ii) $q = 0$,

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

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

where λ>0 now represents the shadow value of biomass to the recreational fishermen

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

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

$$G(x) = y.$$

Conservationists

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

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

$$\text{Subject to: } \dot{x} = G(x) - q - y \, .$$
$$q, y \geq 0$$

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

(i) $\lambda \geq 0,\ q \geq 0,\ q \cdot \lambda = 0$,

(ii) $\lambda \geq 0,\ y \geq 0,\ y \cdot \lambda = 0$,

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

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

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

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

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

$$G(x) = q.$$

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

$$B_x(x^*)=0,$$

$$G(x^*) = z=q+y.$$

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

$$G(x) = 0,$$
$$y=q=0.$$

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: $p\cdot q - c\cdot \frac{q^2}{x}$,

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

Recreational fishers: $\varepsilon\cdot y - \phi\cdot \frac{y^2}{x}$,

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

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

Parameter values are as follows:

Parameters	Values
α	2
β	1
p	1
c	1
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	1.64	0.59	0
Recreational fishers	1.73	0	0.47
Conservationists	2.0	0	0

It may be added that under open access equilibrium, only the commercial fishers will prevail with sustainable biomass and harvest both equal to unity.

Appendix 3

Operation of the ITQ system

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

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

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

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

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

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

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

Necessary conditions to solve this problem include the conditions:

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

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

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

The first condition requires all active fishers (the inactive ones are not excluded from the fishery) 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 jointly determine the optimal total harvest at each point of time and the corresponding shadow value of biomass. For simplicity (although this is not entirely accurate) we may imagine that these conditions, i.e. (ii) and (iii) are first solved to determine the optimal total harvest (TAC) and shadow value of biomass. Then, on that basis, equations (i) are solved to determine the optimal allocation of the TAC to individual firms.

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

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

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

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

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

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

Note that as regards solving the maximization problem, the 2nd constraint is redundant as it contains no variables the fisher can influence.[12]

Necessary conditions to solve this problem are for all active fishers:

[12] Note that it is never optimal for any fisher to leave a quota unused.

(i´) $\sigma(i) = s$.
(ii´) $\dot{\sigma}(i) - r \cdot \sigma(i) = -\Pi_{q(i)} \cdot Q$.
(iii´) $\dot{\alpha}(i) = z$.

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

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

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 proves that the ITQ system generates allocative efficiency at each point of time. If, moreover, the expression $\dfrac{r \cdot s - \dot{s}}{Q} = \lambda$, the fishery will also follow the optimal biomass path over time. This will happen if the TAC, i.e. *Q*, is set correctly at each point of time.

Appendix 4
Conservation under the ITQ system

In this appendix we only need to consider inter-sectoral quota trades, i.e. trades between fishers and conservationists. We don't have to consider quota trades within the group of fishers since we already established in Appendix 3 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:

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

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

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

Where $B(x;i)$ is the benefit function of conservationist *i*, $z(i)$ his purchases of quota shares 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, i.e. a conservationist active in the quota market but not having all the quotas ($\beta(i)$, $\sum_j^J \beta(j) \in (0,1)$, 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:

(A4.1) $$v = \frac{B_x(x;i)}{(r - G_x(x))} \cdot \frac{Q}{r}\,.$$

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

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

subject to essentially the same constraints as the individual conservationists.

The necessary conditions include:

(A4.2) $$\dot{v} - r \cdot v = -\mu \cdot Q\,,$$

(A4.3) $$\dot{\mu} - r \cdot \mu = -\sum_{j=1}^{J} B_x(x;j) - \mu \cdot G_x(x)\,,$$

where μ is the shadow value of biomass corresponding to the optimal solution for the conservationists as a group. Note that (A4.3) involves the sum of the marginal benefits of biomass for all conservationists while the corresponding differential equation for the individual shadow price, i.e. $\tau(i)$, is restricted to the marginal benefit of biomass to the individual himself. This, of course, is a mathematical reflection of the underlying externality problem.

The equilibrium price of conservation quota share is:

(A4.4) $$v^* = \frac{\sum_{j=1}^{J} B_x(x;j)}{(r - G_x(x))} \cdot \frac{Q}{r}\,,$$

where have have used the '*' to indicate the conservation quota price for the joinly optimal solution optimal compared to the one generated by individual conservationists. Comparing (A4.4) with equation (A4.1) 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:

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

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 attempt to solve the following maximization problem:

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

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

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

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:

(A4.5) $$v = \left(\Pi_{q(i)} - \frac{\Pi_x}{r - G_x} \right) \cdot \frac{Q}{r} .$$

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

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

subject to essentially the same constraints as the individual conservationists.

The necessary conditions for solving this problem include:

(A4.6) $$\dot{v} - r \cdot v = -\Pi_{q(i)} \cdot Q + \lambda \cdot Q ,$$

(A4.7) $$\dot{\lambda} - r \cdot \lambda = -\sum_{i=1}^{I} \Pi_x - \lambda \cdot G_x ,$$

where λ is the shadow value of biomass to the fishers as a whole. Comparing (A4.7) to the corresponding differential equation for individual fishers, i.e. $\sigma(i)$, reveals a similar externality effect as in the case 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

(A4.8) $$v^* = \left(\Pi_{q(i)} - \frac{\sum_{i=1}^{I} \Pi_x}{r - G_x} \right) \cdot \frac{Q}{r},$$

where have have used the '*' to indicate the fishers' jointly optimal supply price of share quotas for conservation Comparing (A4.8) with (A4.5) 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. In other words, individual supply curves of quota shares for conservation would be higher (demand higher price) that would be optimal for the fishers as a whole. The reason, as before is the stock-externality. Since 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 the conservationists as two independent groups independently maximize their benefits. In that case equations (A4.2) and (A4.3) and (A4.6) and (A4.7) apply. Eliminating the conservation quota share price, v, and the two shadow values of biomass, τ and λ from this system yields after some rearranging:

(A4.9) $$\dot{\Pi}_q - r \cdot \Pi_q = -\Pi_x - B_x - \Pi_q G_x .$$

Expression (A4.9) 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. It is interesting to note that they do not depend on the TAC.

Expressions (A4.2) and (A4.6) imply:

(A4.10) $$\lambda + \mu = \Pi_q, \ \forall t ,$$

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

Combining (A3.1) and (A4.6) yields, after a little rearranging, a useful relationship between the price of a fishing quota, i.e. s (see Appendix 3), and the price of a conservation quota, i.e. 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 if fishing is profitable. It is, moreover, not difficult to show that if Δ>0 in equilibrium and the equilibrium will ultimately be reached, then Δ>0 always.

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