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Ussif Rashid Sumaila

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Summary:
Game theory is a formal tool for analysing strategic interaction between a finite number of agents. The fact that usually more than one entity or agent has property rights to fishery resources, has led to an explosion in the use of game theory and applications thereof to analyse fishery management problems. This review shows that game theoretic modelling has made significant contributions to our understanding of the problems of fishery resource management. However, many challenges still remain. For instance, models of straddling stocks are yet to be fully developed. In addition, fisheries economists have not yet fully exploited the opportunity provided by computational methods now available, and the ever increasing power of computers, to develop more empirical game theoretic models for practical fisheries management.

Indexing terms:

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To be ordered from Chr. Michelsen Institute, Fantoftvegen 38, N-5036 Fantoft, Bergen, Norway. Telephone: +47 55574000. Telefax: +47 55574166

Introduction

Fish may be classified as *destructible renewable* stock resources, which portray two characteristics.[1] First, "utilisation" of a unit of fish implies its destruction, that is, the unit is irrevocably lost. Second, the fish stock can be augmented to enable a continuing availability through time. Thus, fish (as for other renewable natural resources), have the special feature that even though their utilisation results in depletion, new stocks are created by a process of self-generation. The regeneration occurs at a 'natural' rate, often directly dependent upon the amount of original stock remaining unutilised. The essence of fishery economics stems from the stock characteristic of fisheries and the fact that the rate of biomass adjustment of a fish stock is a function of that stock[2]. Essentially, the central problem of natural resource economics at large, and fisheries economics in particular, is *intertemporal allocation.* In other words, natural resource economists, are mainly concerned with the question of how much of a stock should be designated for consumption today and how much should be left in place for the future.

The solution to this central problem has been elusive for the following reasons. First, renewable natural resources are often "common property", in which several entities have property rights to the resource. In particular, certain fisheries are transboundary and/or straddling in nature.[3] Second, some species of fish are long lived, such that whether juveniles or mature fish are caught can have important biological and economic consequences. Third, in multispecies systems, there is usually some form of natural interaction between species, which have both biological and economic consequences. Fourth, different vessel types employed in the exploitation of the resource have different effects on the health of the stock, and the economics of the fishery. Fifth, capital embodied in the exploitation of natural resources are often non-malleable, which can impact on management plans. Sixth, there is the problem of uncertainly about the biology and economics of the resource. Seventh, we must deal with the problem of market interaction in both factors and products. As demonstrated in the sections that follow, the fisheries economics literature is rich in attempts to address these problems.

Models of fishing

Open access and sole ownership fishery models

Economists have traced the main problem of the fishing industry to its unique "common property" characteristics.[4] The first comprehensive analysis of this problem was by Gordon.[5] The common property characteristics of the fishery is necessarily associated with both open access and the lack of delineated right to the fishery.[6] Earlier published analyses of fisheries economics[7,8,9,10,11,12] have been concerned with two contrasting systems of property rights: (i) full rights and (ii) no rights. These two systems yield unique "Nash non-cooperative outcomes"[13], namely the sole ownership (social planner's) outcome for the former, and the open access outcome for the latter. The open access or the "tragedy of the commons" outcome is easy to implement but most wasteful. A solid theoretical discussion of this outcome is given in [9]. The social planner's outcome, by reducing play to a sole owner, is almost impossible to realise in practice because of the constant threat of new entrants into the fishery. The sole ownership equilibrium, however, has excellent efficiency properties. It is usually used as a reference point for the analysis of real world situations.

Game theoretic models[14]

Game theory is a mathematical tool for analysing *strategic interaction.* For example, suppose a few firms dominate a market, or a few group of individuals or entities have fishing rights to a common property resource, or countries have to make an agreement on trade or environmental policy. Each agent in question has to consider the other's reactions and expectations regarding their own decisions.

With the development of game theory[15] came its use to analyse problems not only in economics but also in such diverse areas as political science, philosophy, and military strategy. [16] Currently there is an explosion in the use of game theory and applications thereof in virtually all areas of economics.

Game theoretic fisheries models are made up of a combination of a biological model of fisheries and one of the solution concepts of Nash, or their refinements. The biological models underlying such game theoretic models can be classified into two main categories [17]. First, Models of the *lumped parameter* type, for which the models of Ricker[18] in discrete time, and of Schaefer[19] in continuous time, are the most widely used. Second, the so-called *cohort models*, which explicitly recognise that fish grow with time and suffer natural mortality. The most commonly used model in this class is that of Beverton and Holt[20]. [17] argues that both the age at which fish are captured and the relationship between parent stock and recruitment play an important role in determining yields in many commercially important fisheries. Therefore, it would seem reasonable to consider optimal harvesting using a model which incorporates both a cohort structure and dependency of recruitment upon parent stock. One model with both of these characteristics is the Leslie matrix model[21].

Cooperative and non-cooperative management

Nash[22] was the first to explicitly distinguish between cooperative and non-cooperative games. He classified games in which binding agreements are not feasible to be non-cooperative, and those in which binding agreements are feasible, cooperative games. Both of these types of games have been used to analyse the exploitation of fishery resources. Usually, models are developed to study what happens both to the biology and economics of a fishery under cooperation and non-cooperation, with the aim of isolating the negative effects of non-cooperation[23].

In undertaking a cooperative management analysis, Munro[24] combined the standard economic model of a fishery with cooperative game theory. It is shown in this study that if the cooperative management is unconstrained, that is, if allowances are made for time variant harvest shares and for transfer payments, then to achieve optimal joint harvest demands that the patient player should buy out its impatient partner entirely at the commencement of the program and manage the resource as a single owner[25]. Thus, achieving what Munro calls an *optimum optimorum*[26]. Sumaila[27] develops an applied computational game theoretic model in which two vessel types are organized as separate agents, who exploit a shared stock (the Arcto-Norwegian cod stock). The results of this study confirms the main theoretical findings of [24].

The analysis of cooperative non-binding programs is more difficult [25]. The key to the solution of such programs is for each player in the game to devise a set of "credible threats"[28]. Kaitala and Pohjola[29] provide a good example of non-binding cooperative management. In their model, the management program is modelled as a differential game in which memory strategies are used. Vislie[30] developed a simplified version of [24], which he used to derive a self-enforcing sharing agreement for exploiting transboundary renewable resources in cooperative without strictly (judicially) binding contracts.

Krawczyk and Tolwinski[31] consider a feedback solution to an optimal control problem with 9 control variables for the Southern Bluefin Tuna (SBT). Kennedy and

Watkins[32], instead, consider a cooperative solution for the SBT management problem modelled as a 2-agent, optimal control problem with linear dynamics. Both papers use multi-cohort biomodels to determine optimal time dependent quotas. To solve their models both studies employ the perturbation method developed in Horwood and Whittle[33].

Dynamic externality

Dynamic externality is the bioeconomic loss which arises when a single dynamic population is exploited by a finite number of fishers. [23] study this kind of externality by using the concept of Cournot-Nash equilibria. Clark[34] considered a limited access fishery as an N-person, nonzero-sum differential game. Sumaila[35] uses computational game theoretic models of fishing that study the consequences of dynamic externality. All these papers show that, no matter the details of the models developed, the negative bioeconomic effects of dynamic externality are quite significant.

Market externality

Dockner *et. al.*[36] presented a generalised Gordon-Schaefer fishery model to a duopoly. The main difference between this model and "no-market" interaction models, such as [34,35] is that it is an oligopolistic model rather than a competitive market output one[37]. It assumes that the price of landed fish is not constant but depends on the quantity harvested by all producers, implying that the interaction at the marketplace, while not the only interaction between agents, is important. The paper studies the impact of different oligopoly strategies, namely Nash and Stackelberg, on prices, quantities and payoffs to the players. The authors set up a non-cooperative game which they solve both analytically and numerically by using the equilibrium concepts of Nash and Stackelberg. Their analysis shows that in both the Nash and Stackelberg cases, the player with the smaller unit cost is able to choose higher catch rates than his opponent. They also find that the game is Stackelberg dominant. This means that the payoffs to both players are higher in the Stackelberg case than in the corresponding Nash case. Another finding of theirs is that in the Stackelberg case any information disadvantage in the sense of Stackelberg followership can be eliminated by a more efficient technology.

Multispecies interaction externality

Quirk and Smith[38] and Anderson[39] were among the first theoretical papers to appear in the fisheries economics literature on ecologically interdependent fisheries. Both study and compare the free access equilibria and the social optima in such systems. They derive necessary conditions for optima and interpret these in general terms. Hannesson[40] extends the results of these two papers to address broader questions such as, is there a price at which it is economically sensible to switch from exploiting the prey to exploiting the predator in such systems?

Fisher and Mirman[41] and Flaaten and Armstrong[42] are theoretical papers which analyse interdependent renewable resources using game theoretic models. These papers assume single cohort growth rules to derive general theoretical results. The study of Sumaila[43] is an empirical study of the Barents Sea fisheries, which explicitly recognises that fish grow with time and that the age groups of fish are important both biologically and economically. Another study of problems in strategic context is Clemhout and Wan[44].

Transboundary/migratory/straddling stock models

One can distinguish between three types of transboundary fishery resources. First, fish stocks that migrate between the EEZ of two or more coastal states, which may be considered transboundary resources "proper". Second, highly migratory stocks, which in effect refers to tuna. Third, the so-called "straddling" fish stocks, that is, those stocks that migrate between the EEZ of one or more coastal states and the high seas[45].

Analysis of the management of transboundary resources "proper" is treated in Munro[46], McRae and Munro[47], Munro[48], and [27]. [42] and Flaaten[49] are treatments of transboundary fishery problems involving Norway and the former Soviet Union. Recent contributions in the area of migratory fisheries are: Munro[50]; Arnason[51] and [41]. It is demonstrated in [24], [34] and Levhari and Mirman[52] that, whatever the scenario we choose, the outcome to the fishing nations of non-cooperation is of unquestioned undesirability [25]. This is because the outcome is simply Pareto inefficient, implying that the payoff to some of the players can be increased without necessarily decreasing those of others.

The theory of transboundary fishery resources has been used in the context of different user groups and/or vessel types exploiting a shared stock. [26] and [35] are examples where studies of the exploitation of a shared stock are organised around the vessel types employed in the exploitation of the resource.

Recent conflicts, such as those between Canada and the EU over stocks straddling between Canada's EEZ and the high seas, have generated interest among fisheries economists on the management of straddling fish stocks, with Kaitala and Munro[53] leading research efforts. Their work has thus far shown that the non-cooperative theory developed for the study of transboundary resources also applies to straddling stocks. This is, however, not the case when it comes to cooperative theory. Here, the cooperative theory of transboundary resources breaks down because of the so-called "entry-exit" problem implied by the "Draft Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 Relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks"[54].

Malleable and non-malleable capital models

A number of papers have appeared in the fishery economics literature that focus, in part, on the irreversibility of capital employed in the exploitation of fishery resources. Examples include Clark *et al.*[55], Clark & Kirkwood[56], Dudley & Waugh[57], Charles[58], and Charles & Munro[59]. Among these examples only [57] considers, qualitatively, investment decisions in a fishery with more than a single agent. [35] provides a quantitative analysis of a two-agent fishery where the irreversibility of capital is the central assumption. The negative economic effects of irreversibility of capital were shown to be significant.

Fisheries management models with uncertainty

Uncertainty is certainly an obstacle for sustainable fisheries management, the main sources of which include; firstly, the dynamic nature of fish populations in the wild and the variability and complexity of the marine ecosystems of which they are a part, and secondly, the impact of fishing activity upon the resources, and the fact that perfect monitoring and control of harvesting in marine capture fisheries will forever be problematic.

Uncertainty has been classified into two broad categories[60]. First degree uncertainty consists of "random effects whose future frequency of occurrence can be determined from past experience"[61]. Hence, it is possible to construct objective probability distributions to capture this class of uncertainty. Second degree uncertainty, usually termed "true uncertainty", covers events that cannot be predicted, and for which objective probability cannot be estimated [60]. It is possible to reduce this class of uncertainty through further research but to eliminate it completely is but a dream: There will always exist an irreducible level of uncertainty.

To date most stochastic economic models of fisheries incorporate only first degree uncertainty.[62] Protected marine reserves (PMRs) have been advanced as a viable tool for dealing with second degree uncertainty. A key effort in this direction is the work of Lauck *et al*[63]. This paper has explicitly linked the mitigation of second degree or true uncertainty to the creation of PMRs. Many biological papers have promoted the establishment of PMRs as a viable alternative where other forms of fisheries management are impracticable or unsuccessful[64]. It remains to be seen what bioeconomic models of marine reserves will demonstrate about the use of marine reserves to hedge against uncertainty[65].

Computational methods

The key to the empirical applications in fisheries economics of the theoretical assertions of game theory is the development of computational techniques for identifying the equilibrium solutions it predicts. Three types of equilibrium concepts or informational assumptions are used in game theoretic models; *open loop*, *feedback*, and *closed loop*. With open loop information in dynamic games, players cannot observe the state of the system after time = 0. Even if they can, it may not be possible for them to do anything about it. In other words, they can commit to their controls only at the start of the game. Feedback and closed-loop are rules for choosing controls as functions of the state (stock). The difference between the two information structures is that with feedback controls, which are Markovian in nature, players know only the current state (that is, the pay-off relevant actual information), whereas closed-loop information includes the way in which the stock has evolved so far in the game[66]. Feedback and closed loop controls allow the player more rationality and flexibility but due to the difficulty of computing these solutions, there has been a tendency in the literature to resort to the use of open loop solution concepts[67]. There are other reasons for the continued used of the open loop equilibrium concept in the literature. In the first place, more rationality and flexibility does not necessarily mean that closed loop solutions are always better than their open loop counterparts. In the discussion of rules, or open loop in our context, versus discretion, or closed loop in the macroeconomics literature, rules are shown to often produce more desirable outcomes than discretion[68]. Second, the open loop solution concept can be used with a more complex information structure, known as *piecewise deterministic games*[69].

Many algorithms for the computation of economic equilibria have been presented in the computational literature[70]. Examples of methods for computing game theoretic equilibrium solutions are the perturbation method of Horwood and Whittle[71] , the methods used to construct and estimate game theoretic models of oligopolistic interaction [66], methods for computing cooperative equilibria in discounted stochastic sequential games[72], and algorithms from nonsmooth convex optimisation, in particular, subgradient projection and proximal-point procedures[73]. The latter class of algorithms are intuitive because they are "behavioristic", modeling out-of-equilibrium behaviour as a "gradient" system driven by natural incentives.

Concluding Remarks

In terms of policy, this paper shows that results derived from game theoretic models of fishing have produced insights that have been beneficial to the practical management of the world's fishery management. Such models have, by revealing the negative consequences of non-cooperation, contributed in encouraging and sustaining the joint management of tansboundary fishery resources in particular. Typical examples are the mutually beneficial management of the Northeast Atlantic cod stock by Russia and Norway, and the joint management of the Southern Bluefin Tuna by Australia, Japan and New Zealand. This review has also shown that while much has been achieved through the use of game theory in analysing fishery management problems, more needs to be done. Models for the conservation and management of high sea fisheries need to be fully developed, especially, with respect to determining viable cooperative solution outcomes. In addition, great opportunities are available for more empirical game theoretic modelling of fisheries management problems, by combining the many solution procedures currently available in the computational and simulation literature with the ever increasing power of computers to address important fishery management problems.

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[14] Almost all the papers cited in this survey develop simultaneous-move games. It is worth mentioning that sequential-move fishery game models are beginning to appear in the literature, a recent example is R. Hannesson, 'Sequential fishing: cooperative and non-cooperative equilibria', *Natural Resource Modeling* 9(1), 1995, pp 51-59.
[15] U.R. Sumaila, 'Essays on the application of game theory in the management of natural resources', *Dissertations in Economics* No 12, 1996, Department of Economics, University of Bergen, Norway, presents the main mileposts in the historical development of the theory of games.
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