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An Overview of Bioeconomic Analysis and Management in Fisheries

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Abstract: This study provides an overview of the bioeconomic analysis and different management techniques for fisheries. A variety of bioeconomic analysis that affect the fishery as a whole is examined. It also presents the potential benefits and draw backs of different management tools. In general, the study finds that some management tools are equivalent and suggests that combinations of some management tools may be more useful for fisheries management. We also analyze optimal harvesting policy in a general framework of both single species and multi species fishery.

Key words: Fisheries management, individual transferable quotas, marine protected areas, taxes, adaptive management, feedback control

Introduction

Fisheries are managed because the consequences of uncontrolled fishing are seen as undesirable. These consequences could include fishery collapse, economic inefficiency, loss of employment, habitat loss or decreases in the abundance of rare species. Fisheries scientists tried to provide advice that could be used to prevent the over exploitation or collapse of fished stocks. However, the increasing intensity of fishing throughout the world has had impacts on the marine ecosystem and these impacts are now the focus of many research and management progress.

Traditionally, the full utilization of fish stocks for profit maximization has been the key goal of fishery management and development, putting protection and conservation of the valuable ocean resources in the backseat. The problem of over-fishing is a serious one and unless something is done, the consequences will be disastrous. We thus put forth a proportion aimed at fisheries management by way of addressing high government subsidies, monitoring schemes, demand-led measures, public information campaigns and technology restrictions, while integrating the fish consuming public, fisherman and above all, the environment. Human activities are the primary cause of marine resource degradation. Pollution, deforestation, shipping, dumping, mining, oil production, chemicals, refuge, habitat alteration introduction of non-native species and global climate change are all important agents of change in the marine environment. Now, however, more damaging to the important fish populations is the over-fishing. By 1994, 70% of the world's marine fish stock were either fully to heavily exploited, overexploited, depleted or slowly recovering from previous fishing (FAO, 1994).

The principal, direct impact of fishing is that it reduces the abundance of target species. It has often been assumed that this does not impose any direct threat of species extinction as marine fish generally are very fecund and the ocean expanse is wide (Pitcher, 1998). But the past few decades have witnessed a growing awareness that fishes can be severally depleted, even be threatened with extinction through over exploitation (Casey and Myers, 1998). Among commercially important species, those particularly at risk are species that are highly valued, large and slow to mature, have limited

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geographical range and/or have sporadic recruitment (Sadovy, 2001). There is actually little support, though, for the general assumption that the most highly fecund marine fish species are less susceptible to over exploitation; rather it seems that this perception is flawed (Hutchings, 2000a). Fisheries may also change the evolutionary characteristics of populations by selectively removing the larger, fast-growing individuals and one important research question is whether this induces irreversible changes in the gene pool (Law, 2000). Overall, this has implications for research, monitoring and management and it points to the need for incorporating ecological consideration in fisheries management (Gislason *et al*., 2000, Hutchings, 2000b), as exemplified by the development of quantitative guidelines to avoid local extinctions (Punt, 2000).

For many years, the main objective of fishery management was to maximize the yield taken from a fishery without compromising future catches. But now fisheries science is a more exciting and varied field of study than ever before. This is because contemporary management objectives are increasingly diverse and our attempts to manage and conserve fisheries are based on a much broader scientific understanding of fishers and the fished ecosystem. Indeed, many fishery scientists are now asked to address biological, economic and social concerns.

This study provides an overview of the bioeconomic analysis and different management techniques for fisheries. A variety of bioeconomic analyses that affect the fishery is discussed. In general, the review finds that some management tools are equivalent and suggests that combinations of some management tools may be more useful for fisheries management.

Bioeconomic Analyses

Bioeconomic models are frequently constructed to evaluate management strategies, consisting of a biological component for the dynamics of a population and an economic component for the characteristics and possibly dynamics of the harvesting sectors. Economic objectives incorporate price and cost information and may involve a discount rate. Gordon (1954) made one of the first attempts to produce an economic analysis of a fishery when he tried to explain why Canadian fisheries had such low incomes. His analysis was very important because it suggested why an open-access fishery be over-fished and provide poor economic returns for the fishers.

The total revenue is determined by two things: the market price of the resource and the total number of resource produced (or the yield):

$$\text{Total Revenue} = \text{Price} \times \text{Yield}$$

The yield of the resource will involve two things: the effort spent in harvesting the resource and the abundance of resource, denoted by E and x, respectively. As a result, we can say:

$$\text{Yield} = qEx,$$

where q is termed the catch ability coefficient. This would represent environmental factors that limit (or enhance) our ability to harvest the resource at the best of our abilities. Effort E could be measured in the number of boats at the fishery, interval of fishing season or others.
So if market price for the resource is p, then we have:

$$\text{Total Revenue} = \text{Price} \times \text{Yield} = pqEx$$

The total cost of harvesting the resource is proportional to the effort exerted:

$$\text{Total Cost} = cE,$$

where c is a constant that represents external controls on cost (such as the price of fuel to power motors).

As a result, the profit of harvesting the resource (or the total economic rent) is given by:

$$\text{Economic Rent} = pqxE - cE.$$

Bioeconomic analysis, for example, can help to determine optimal fleet sizes, configuration and employment, whether catch limits should be fixed or variable and how taxation or licence fees would influence fishing effort.

The Basic Fishery Model

In accordance with classical modeling, the growth of the biomass density is given by:

$$\dot{x} = F(x) - h(t) = F(x) - qEx(t) \tag{1}$$

where $F(\cdot)$ is the natural density growth function and $h(t)$, the capture rate.

The standard economic theory claims that fishery managers maximize the profits from harvesting, which amounts to deal with the following optimization problem

$$J = \max_{E(\cdot)} \int_{t=0}^{\infty} e^{-\delta t}(pqx(t) - c)E(t)dt$$

$$\text{s.t. } \dot{x} = F(x) - h(t) = F(x) - qEx(t) \qquad x(0) = x_0 \tag{2}$$

$$0 \le E(t) \le E_{max},\ 0 \le x(t) \le k \tag{3}$$

where k is the carrying capacity and $\delta > 0$ is the instantaneous discount rate.

According to Eq. 2, for all trajectories s.t. $x(t) \neq 0$ for any $t \geq 0$, we obtain the following calculus of variations problem over an infinite horizon (4), equivalent to J:

$$\max_{x(\cdot)} \int_{t=0}^{\infty} e^{-\delta t}\left(p - \frac{c}{qx(\cdot)}\right)(F(x(t)) - \dot{x})dt \tag{4}$$

where $x(\cdot)$ belongs to some space of paths (piecewise continuously differentiable functions s.t. the improper integral converges and constraints (Eq. 2, Eq. 3) are satisfied. If an interior solution exists, it must satisfy the classical Euler necessary condition, which takes here the following expression.

$$\left(\frac{pqx(t)}{c} - 1\right)(\delta - F'(x(t))) - \frac{F(x(t))}{x(t)} = 0 \tag{5}$$

It is well known that in this singular case, i.e., when (Eq. 5) determines an unique stationary path x^*, the optimal solutions are the most rapid approach paths to x^* (Clark, 1990).

When an optimal stationary solution x^* exists, the associated optimal fishing effort E^* satisfies

$$E^* = \left(\frac{pqx^* - c}{cq}\right)(\delta - F'(x^*))$$

with the profit

$$J^* = \left(\frac{pqx^* - c}{\delta}\right)E^*$$

If $pqx^* \geq c$, E^* is feasible (i.e., nonnegative, assuming $f(x^*) < \delta$) and the fishery profit is nonnegative. If $pqx^* < c$, E^* is negative. The profit associated to any feasible value of stationary E is non-positive. The optimal solution consists in no fishing.

Harvest control may be fixed or time dependent. It is fixed in the sense that the parameters for the controls are constant in time. Harvest control may be time varying in the sense that a different harvest control value is selected for each year in the future. Harvest controls can vary over time for a number of reasons, e.g., due to nonstationarity in the dynamics or environment, such as harvest controls linked to time dependent environmental cycles (Parma, 1990); more generally, controls vary because they are part of an adaptive management scheme (Walters, 1986).

Fan and Wang (1998) proposed and analyzed a model to study the exploitation of a single fish population modeled by logistic equation with time dependent coefficients. Optimal harvesting effort that maximizes the annual sustainable yield is obtained for constant as well as periodic harvests. Pradhan and Chaudhuri (1998) discussed the optimal harvesting policy of a single-species fishery with Gompertz law of population growth. Dubey *et al*. (2002) proposed a dynamic model for a single species fishery that depends partially on a logistically growing resource. They showed that both the equilibrium density of fish population and the maximum sustainable yield increase as the resource biomass density increases.

Recently, Zhang *et al*. (2003) obtained optimal harvesting policy for a single population with logistic growth and impulsive harvesting. They studied existence and global attractiveness of impulsive periodic solutions for constant and proportionate harvesting and obtain optimal effort policy to maximize the sustainable yield. They compare the continuous harvest policy with impulsive harvest policy and find that the continuous harvesting policy is superior to the impulsive harvesting policy. Dong *et al*. (2006) obtained the optimal harvesting policy for a single population with periodic gompertz growth and impulsive harvesting. Matsuda *et al*. (1999) obtained the optimal fishing season and the first age at capture of a fish that has a limited spawning season. They also compare the continuous harvest policy with impulsive harvest policy and find that both are almost equals. Brauer and Sanchez (2003) considered autonomous population models under periodic harvesting and population models in periodic environments. They showed that for an autonomous population model with constant rate harvesting there is either an asymptotically stable equilibrium or extinction of the population, depending on harvest rate, on the otherhand, under periodic harvesting and fairly general conditions the behavior is analogous, but with an asymptotically stable periodic solution instead of an asymptotically stable equilibrium. For periodic population models they have examined some special cases in which there is an asymptotically stable periodic solution.

The importance of knowledge on how a species behaves in its habitat must not be ignored and is vital to sustaining the fishery. For this reason, modeling the interdependency between fish populations is especially relevant towards providing a greater amount of realism.

There is another approach in single species fishery models with a variety of uncertainties. There are at least two types of uncertainties in fisheries, (i) observation, (ii) process uncertainties (Hilborn and Mangel, 1997). Process uncertainties are characterized by stochasticity in recruitment and other life history parameters. An optimal harvesting strategy with process uncertainties is known as the “constant escapement, under which the stock after fishing season should be kept constant (Reed, 1979). However, the constant escapement strategy is vulnerable to observation errors. Recently a more robust rule against observation errors and mismeasurement of life history parameters and carrying capacities is saught (Katsukawa, 2004).

Multispecies Fishery

Since all components in the marine ecosystem are interlinked, it is impossible to change one component without affecting everything else. There are two main aspects of multispecies theory:

biological interactions among species and technical interactions through fishing fleets catching more than one species at a time. If one particular species of fish is heavily over-fished, the entire ecosystem, in which that fish occupied a particular niche, is affected. In an extreme case, a competing species may take advantage of the vacant niche space and food resources left by the exploited fish. This may cause a population boom in the second species and prevent the first species from ever being restored to its former abundance. Even species that are not directly commercially exploited are likely to be affected by the removal of a substantial proportion of their prey, predator or competitor.

Assume that fisheries management maximizes the present value of future harvests $h_i(t)$, $(i = 1, 2, \ldots, n)$. In the following we rely on the standard modeling framework where harvest $h_i(t)$ is a linear function of effort $E_i(t)$ and stock size $x_i(t)$, i.e., $h(t)= q_iE_i\, x_i$. Furthermore, there is a constant fish price p_i. The regulator is maximizing the discounted value of future profits with discount rate δ, i.e., the problem becomes

$$\begin{cases}\max \\ \{E(t)\}\end{cases} \int_{t=0}^{\infty} e^{-\delta t} \sum_{i=1}^{n} (p_i q_i x_i(t) - c_i) E_i(t) dt, \quad E(t) = (E_1(t), \ldots., E_n(t))$$

subject to
$$\dot{x}_i = F_i(x) - h_i(t) = F_i(x) - q_i E_i x_i(t), \quad x = (x_1, x_2, \ldots. x_n),\ i = 1, 2, \ldots., n$$
$$0 \le E_i \le E_{i\max}$$

The current value Hamiltonian for this environment is constructed as follows:

$$H = \sum_{i=1}^{n} (p_i q_i x_i(t) - c_i) E_i(t) + \sum_{i=1}^{n} \lambda_i (F_i(x) - q_i E_i x_i)$$

The derivation is similar to the single-species case in the previous section. The only adjustment from the single species case is the growth functions $F_i(x)$ are now potentially interdependent.

One can distinguish of species interaction in some different ways, but competition and prey-predator are the most common for fisheries. In the independent species case, harvest decisions for each species are made without regard to the existence of the other species. In this respect, a multispecies model would yield the same results as independently developed single species models. The behaviour of the predator-prey model is known to be very sensitive to the form and parameters in the growth functions. Hannesson (1982), Clark (1990) and Strobele and Wacker (1995) analyze some economic aspects of a predator-prey system. Deriving two symmetric Golden Rules from a prey-predator system, Imeson *et al*. (2002) showed that, the term accounts for the cost decrease in prey harvesting when extra predators are fished. The prey are less eaten so the prey stock size increases, which in turn makes fishing less costly. Conversely, fishing more prey causes predators to starve, resulting in a lower stock size and an increases in the cost of fishing. Wacker (1999) studied harvesting in a mutualistic ecosystem. Mutualistic systems behave completely different from predator-prey systems.

Clark (1990) studied the combined harvesting of two ecologically independent populations. His analysis shows that when two populations are exploited jointly, one population may be driven to extinction, whereas the other population continues to support the fishery in bionomic (one species) equilibrium. Chaudhuri (1986), presented the problem of combined harvesting of two competing fish species, each of which obeys the law of logistic growth. It is also shown that the open-access fishery may possess a bionomic equilibrium which drives one species to extinction. Mesterton-Gibbons (1996) described a technique to find the optimal harvesting policy for a Lotka-Volterra ecosystem of two interdependent populations when harvest rate is proportional to harvesting effort and either a single stock is selectively harvested or both stocks are harvested together. A problem that yields to this technique is Chaudhuri (1986) previously unsolved problem of harvesting two competing species. The solution reveals that even if two species would coexist in the absence of harvesting, one species may be driven to extinction by the optimal policy if it is sufficiently more catchable than the other. He suggested that the technique may be widely applicable in ecological modeling. Kar and Chaudhuri (2004) proposed a two competing species which are affected not only by harvesting but also by the presence of a predator. They also showed that even after the extinction of one prey, the other prey continues to support the prey-predator fishery in bionomic equilibrium. They also discussed the optimal harvesting policy for the same problem. Song and Chen (2001) considered the exploitation of two competitive population models of stage structure with a mature population of harvesting. They obtained conditions for the existence of a globally asymptotically stable positive equilibrium and a threshold of harvesting for the mature population.

The question of permanence of biological species is of particular interest to fishery. If it is known that a system exhibits such a permanent behaviour, then ecological planning based on a fixed eventual population can be carried out. Analyzing the problem of prey-predator model with stage-structure for predator, Kar (2005) obtained some conditions for permanence of their system.

Management Strategies

Governments and other authorities manage fisheries because the biological, social and economic consequences of an unregulated fishery are undesirable. Their managements objectives may be intended to ensure the economic and social well being of future generations or to protect habitats and species of conservation concern. Effective fisheries management requires clear objectives supported by the best scientific advice and appropriate management actions.

In practice, the management of a fishery is a decision with multiple objectives. Some of the desirable objectives in the management of fish resources are as follows:

(I) The provision of good bio-mass yield, (ii) The conservation of the fish population, (iii) The conservation of the genetic variability of the fish population, (iv) The provision of good economic returns, (v) The provision of steady employment. Thus, the fisheries scientist has to understand links between different disciplines and the ways in which science can usefully inform the manager.

The formulation of good harvesting policies that take into account these objectives is a complex and difficult task even when the dynamics of a fish population are known accurately. The objectives are fully quantified.

The necessity of a regulation policy for fishery management is recognized today. In order to find a reasonable strategy which guarantees a lasting exploitation of the resource, there have to be a compromise between the maximization of the benefit resulted from fisheries and stocks perenniality. On the one hand it must avoid exhausting the navy resources and on other hand it should guarantee a maximum level of harvesting. But, the transition from an overexploitation of the resource to a stabilized situation is globally hard to achieve.

Maximum Sustainable Yield (MSY)

The MSY is a simple way to manage resources taking into consideration that over-exploiting resources lead to a loss in productivity. When the rate of exploitation increases in a fishery, we see that at first there is an almost proportionate increase in total catches. Then this growth rate drops in steadily and the curve finally shows a maximum level (maximum sustainable yield or MSY). Its success can be explained by the simplicity of the model which did much to convince administrators of the need to limit fishing andtherefore UNCLOS (United Nations Convention of the Sea) refers to the MSY. In international fisheries where the various national authorities each had to defend the rival interests if their fishermen and their respective fishing industries and tried to obtain the most advantageous catch quotas, the MSY was the option involving the least reduction in catches and catch methods in a fishery that was already being overexploited. Despite of such a simplicity, some reasons why the MSY is not attained have been shown (Clark, 1990; Hilborn, 2002).

The main problem of the MSY is economical irrelevance. It is so since it takes into consideration the benefits of resource exploitation, but completely disregard the cost operation of resource exploitation. For example, it ignores the fact that if a species is harvested such that its population decreases to a certain level, then the cost of harvesting can become exorbitant because finding the desirable resource becomes more time consuming. This might lead to a situation where the cost of harvesting is higher than the benefit. Therefore, it is of interest to analyze a resource-based economy in a framework that seeks to investigate the effects of distortions for the economy as a whole.

Ecosystems are characterized by the influence of the various factors, both natural and those caused by fishing, which could have operated in the collapse of many fisheries in recent years. Such factors include the effects of long term climatic fluctuations on the geographic distribution of resources and the biotic capacity of the environment, the natural variability of stocks which is often higher with coastal pelagic species, a drop in recruitment due to over-fishing of parent stock, an increase of natural variability due to fishing, etc. However, the classical MSY theory does not include these factors. Also we have seen that the traditional approach to fisheries management relies on single species models of population dynamics that aim to sustain harvests of commercial species. Such an approach ignores a broad suite of interactions among exploited species and between exploited species and other members of their communities. Recently, Matsuda and Abrams (2006), argued that MSY theory does not always guarantee species coexistence even for simple predator-prey systems. To study the usefulness of MSY theory in foodweb systems, they investigated simple 3 and 6 species foodweb models and defined unconstrained MSY and constrained MSY as the maximal yields from the entire biological community when extinction of some species is either allowed or is not allowed. They showed that at the unconstrained MSY solution, it is rare for all species to coexist and the constrained MSY for a particular food web is equal to or smaller than the unconstrained MSY for the same foodweb. Although the MSY, according to the above, is suboptimal from both economic and foodweb perspective, it provides a clearly defined objective of management that delimitates over-fishing (Gulland, 1983). If the catch is effected by effort larger than the one needed to catch the MSY amount, then the fishery is considered biologically over-fished (Munro and Scott, 1985). To know more about MSY, Schaefer (1954), Bagachwa *et al*. (1994), Gallastegui (1983) and Hannesson (1989).

Taxes and Subsidies

Regulation of exploitation of biological resources has become a problem of major concern nowadays in view of the dwindling resource stocks and the deteriorating environment. Economic progress and ecological balance always have conflicting interests. For the necessities of human beings invariably robs the ecological structure of the nature and leads to extinction of several species. Often it is possible to prevent such extinction by force or dissentive. Exploitation of marine fisheries naturally involves the problems of law enforcement. Various aspects of law enforcement in regulating fisheries have been discussed by Sutinen and Anderson (1985), Anderson and Lee (1986), Kellog *et al*. (1988) and others. Taxation, license fees, lease of property rights, seasonal harvesting etc. are usually considered as possible governing instruments in fishery regulation. Economists are particularly attracted to taxation, partly because of its economic flexibility and partly because many of the advantages of a competitive economic system can be better maintained under taxation than under other regulatory methods. A single species fishery model using taxation as control measure was first discussed by Clark (1979, 1985, 1990). Single species fishery model based on taxation as a control instrument were also discussed by Chaudhuri and Johnson (1990), Ganguly and Chaudhuri (1995) and Kar *et al*. (2004). It was subsequently adopted in multispecies modeling by Krishna *et al*. (1998), Pradhan and Chaudhuri (1999), Kar and Chaudhuri (2003) and Kar (2004). Kar and Chaudhuri (2003) present a dynamic reaction model in the case of a prey-predator type fishery system, where only the prey species are subjected to harvesting, taking taxation as a control instrument. This imposition of tax acts as a deterrent to the fishermen and helps to control harvesting of prey fish and in turn, it helps the predator to grow. The main aim of this study was to find the proper taxation policy which would give the best possible benefit through harvesting to the society while preventing extinction of the predator. If managers were interested in expediting the rebuilding process of the over-exploited species, a program could be instituted where the over-exploited species landings would be taxed and the under-exploited species landings would be subsidized (Flaaten, 1988). The tax and subsidy needed to keep status quo for the income of the fishermen.

Marine Protected Areas

Most would agree that protected areas are likely to generate new consumptive and non-consumptive benefits as well as research and education benefits and perhaps some existence values. Much of the empirical case study research on the ecological impacts of reserves supports this likelihood, showing that within the boundaries of reserves, populations grow to larger sizes, attain broader age and size distributions and achieve more diverse assemblages. In addition, there is evidence in some cases that the productive quality of the habitat increases, particularly where bottom trawling and dredging were destructive of the substrate. A major challenge exists to evaluate and quantify the net benefits from these beneficial ecosystem changes within newly established and potential reserves.

By contrast to the long-standing and traditional use of marine reserves, the scientific interest and study of the benefits of reserve is relatively recent. For the past few years, there has been a remarkable growth of interest in the literature considering the development of mathematical models to attempt to evaluate the potential benefits that MPAs may be able to provide. However it is noticeable that much of this modeling research has concentrated on the biological effects (Polachek, 1990; DeMartini, 1993; Man *et al*., 1995; Clark, 1996; Guenette and Pitcher, 1999; Hastings and Bostford, 1999; Mangel, 2000). Recently, however, studies of marine reserves have shifted focus towards taking into account the economics of fisheries as well (Holland and Brazee, 1996; Sanchirico and Wilen, 1999, 2001; Brown and Roughgarden, 1997; Hannesson, 1998; Lauck *et al*., 1998; Smith and Wilen, 2003). Hence the possibility of using marine reserves as a fisheries management tool has emerged.

Two core objectives have motivated the establishment of most marine reserves: conservation and sustainable provision for human uses. Conservation goal include, among others (i) biodiversity conservation, (ii) conservation of rare and restricted-range species, (iii) maintenance of genetic diversity, (iv) maintenance and/or restoration of natural ecosystem functioning at local and regional scales and(v) conservation of areas vital for vulnerable life stages. Goals for human uses include (i) managing fisheries (ii) recreation (iii) education (iv) research and (v) fulfilling aesthetic needs.

Roberts *et al*. (2003) established a procedure that allows the evaluation and selection of reserve sites in order to develop functional, interconnected networks of fully protected reserves that will fulfill multiple objectives. They provided a framework that unifies the central aims of conservation and fishery management, while also meeting other human needs such as the provision of ecosystem services. In their scheme, candidate sites for reserves are evaluated against 12 criteria focused toward sustaining the biological integrity and productivity of marine systems at both local and regional scales.

Among the many other factors that contribute to overexploitation of marine fisheries, the role played by uncertainty is important. This uncertainty includes both the scientific uncertainties related to the resource dynamics or assessments and the uncontrollability of catches. Doyen and Bene (2003) studied the influence of protected areas upon fisheries sustainability through a simple dynamic model integrating non-stochastic harvesting uncertainty and a constraint of safe minimum biomass level. They showed formally using a robust approach that, under both certainty and uncertainty, it is possible to identify an ‘optimal’ reserve size which would ensure a maximum guaranteed catch level.

Ami *et al*. (2005), have investigated the impacts of MPAs creation, on both economic and biological perspectives. Their attention has been focused on the obtention of theoretical conditions leading to economic benefits on the sole fishing sector. Optimal migration co-efficient, i.e., the value where potential effect of MPA implementation should be highest, is obtained. Kar and Matsuda (2006a) noticed that the effects of a variation of the migration coefficient is very significant. As migration coefficient increases both the harvesting effort and value function increases. This is a logical conclusion given that if the reserve population fails to migrate into the fishing grounds, the fishery will be devided into two distinct populations and the harvest will be truncated. This contradicts the result of Ami *et al*. (2005), where it is mentioned that the effect of migration coefficient is not very significant.

Sumaila (1998), stated that the establishment of marine reserves has been promoted as a viable alternative when other forms of fisheries management are impracticable or unsuccessful. However, Hannesson (2002) argued that marine reserves alone are not likely to achieve much in economic terms. He also stated that, the migration rate is, of course, critical for the effect of an area closure. A high enough migration rate would virtually nullify any conservation effect of closing off a part of the area. For a low migration rate it would be possible, however, to achieve a substantial conservation effect and to increase the fish yield. Conrad (1999) showed that with no ecological uncertainty and with optimal harvesting, reserve generates no economic benefits to fishers. Such an outcome corresponds to the view of many fishers and also some economists. However, Grafton *et al*. (2005) has showed that marine reserves can simultaneously generate benefits to both fishers and the environment. By incorporating ecological uncertainty into a bioeconomic model and solving for optimal reserve size, they found that reserves are beneficial even with harvesting that tries to maximize the net returns from fishing.

Age and Size of Catches

We know that by changing the average age of the catch (and especially the age after which a species begins to be fished) it is possible to improve the yield of a stock for a given level of effort to some extent and, consequently, to proportionately increases its yield in weight, yield and economic profitability of the fishery. Size limits are used to prevent the harvest of a particular size of fish. Size limits often protect small fish which are immature or have not reached full reproductive capacity, whereas large fish may be protected due to overall importance to reproduction. This is the justification for regulations and gear selectivity, i.e., mesh size of trawls or of gillnets, escape hatch of pots, etc. For instance, we may mention that prediction of Bell and Smith (Townsend, 1986) were inadequate because they predicted that with an increase in effort the lobster population would collapse. This never happened obviously because of the minimum size rule on catch, which their model did not account for. It is clear that optimal harvesting is concerned with both the age of the fish when they are caught and the number of fish caught per unit time. Indeed, the problem of the optimal harvesting of age-distributed populations is very rare. Beverton and Holt (1957) first applied the age structured model to a wide variety of commercial species, including North Sea plaice, Atlantic haddock, Atlantic cod, Yellowtail flounder and Peruvian anchovy. Song and Chen (2001) considered a stage-structured competitive population model with two life stages, immature and mature, with a mature population of harvesting. They obtained conditions for the existence of a globally asymptotically stable positive equilibrium and a threshold of harvesting for the mature population. The optimal harvesting of the mature population is also considered. Kar (2005) considered a prey-predator model with stage structure for predator. He has shown that, if the unharvested system is permanent, then a sufficiently small harvesting rate will not change drastically the qualitative behaviour of the system but region of coexistence shrinks as the harvesting rate increases. The result provides a theoretical support for safe harvesting in biological resource management. Song and Chen (2002) also considered a stage-structure prey-predator model and discussed optimal harvesting and stability. Matsuda and Nishimori (2002) considered a size structured model for the stock recovery program of exploited endemic fisheries resource. Recently, Kar and Matsuda (2006b) considered a harvesting of mature predator species in a prey-predator model. They have also discussed the effects of bycatch of the immature species.

Technical measures in the form of mesh size regulations can be easily monitored and enforced by requiring fishing vessels to show their gear before leaving port. Additionally, management agencies can make illegal the stowing of gears that do not meet the regulatory requirements while at sea. Third, technical measures tend to meet less controversy and resistance from the various segments of the fishing industry. Fishermen may favor technical measures such as increasing the minimum mesh size because they are perceived to be an effective means to protect juvenile fish and curtail by catch and waste. Last, the impact of technical measures can be modeled with relatively easy way than output and input controls.

Catch Quotas

Quotas are specified harvest limits that, once attained, cause closure of the fishery for that species. They may be specified for a particular area, gear type, time period, species, or species group. Total Allowable Catch (TAC) is a concept that has been in use since the early history of fisheries management. In order to regulate the total amount of fish caught, fishery regulation offices can predetermine the amount of fish that can be caught by each fisherman. Each fisherman is then given a certain "quota" he is allowed to catch. TACs have been used in practice as regulatory instruments in the management of many important fisheries. Another instrument which has been proposed by some economists is the ITQs. Currently there are more than 60 property rights-based fishery programs in about 15 countries, which pursue efficiency gains by the creation and allocation of property rights in those fisheries. This implies that 10% of the global ocean fish harvest is currently taken under a property rights management system (Arnason, 2001). Economists see this regulatory instrument as a means of creating property rights. With ITQs each fisher is given a certain proportion of the TACs which may be transferable in whole or in part. This scheme has often been used to address the problem of overcapitalization. It has been implemented in several countries, e.g. Australia, Canada, Iceland, New Zealand and the USA. Although ITQs have been used as instruments for promoting economic efficiency, they may also be used for conservation purposes. In Hormons and Wilen (1997), regulation is split into two stages. In the first stage, a target harvest quota is chosen to ensure stock safety. The quota is then distributed among all the exploiting states. In the second stage, regulatory instruments are selected to achieve the target determined from the quota rule. Weninger and Just (1997) set forth Real Options theory to the valuation of the opportunity to invest in a fishery regulated by means of an Individual Transferable Quota (ITQ) system. They show that while fishers restructuring is immediate with perfect foresight, delayed exit occurs with uncertainty and low opportunity costs of holding ITQs. They pay special attention to the determination of the ITQ trigger price. They obtain the value of waiting by simulation under various degrees of costs inefficiency, interest rates and vessel capital malleability. But ITQs also involve many management difficulties, including the initial quota allocations and the monitoring and enforcement of the quotas. Matsuda and Katsukawa (2002) recommended that the Total Allowable Catch (TAC) for one species should depend on the abundances of other related species. Taxes and ITQs are equivalent in terms of economic efficiency (Clark, 1990), but the distributional implications of these instruments are directly opposite to one another. With taxes, economic rents accrue to the management authority, whereas with ITQs these rents accrue to quota owners. The use of individual transferable quotas in fisheries has been considered an opportunity to achieve a given total allowable catch with a maximum social benefit. One of the assumptions used in obtaining that result is that the system is in perfect compliance. The incidents of non-compliance, however, may affect the performance of transferable property rights-based fisheries in unexplored ways. Chavez and Salgado (2005), analyzed a positive choice model of a fisherman regulated under an individual transferable quota system with opportunities for violations of quota holdings. They have showed that the presence of non-compliance will affect the equilibrium quota price in a very specific manner: it will reduce the equilibrium quota price compared to a full compliance. They also have showed that equilibrium choices of a fisherman depend not only on economic conditions in the fishery, but also on the TACs regulatory control and biological and environmental conditions.

Adaptive Management and Feedback Control

Adaptive management is one of the key concepts for ecosystem management (Holling, 1978; Walters, 1986). All good fishermen learn from their success and failure. A fishermen will try a new fishing method, for example, monitor the results and see how the results compare to what was predicted to happen. Based on the new information, the fishermen may accept the fishing method, may adapt the fishing method to improve on it, or may reject it. This learning and adaptation is the basis for adaptive management. Adaptive management goes one step further and relies on systematic feedback learning and the progressive accumulation of knowledge for improved fisheries management. Thus, adaptive management is an iterative process that consists of an integrated progression of learning by doing. Successive monitoring is indispensable for adaptive management. One of the earliest works of adaptive management was published by Walters and Hilborn (1976). Parameter estimation and dynamic optimization methods were combined for the Ricker stock-recruitment model to show how exploitation rates should be manipulated to give more information about the model parameters. Walters (1997), concludes that the main reasons for the relative low success rates in implementing policies of adaptive management can be attributed to institutional issues. The big hurdle seems to be how to convert the existing institutional structure to make social and ecological systems work in concert. The basic elements of adaptive management are accepted by most researchers. However, there seem to be significant differences regarding their practical implications. A major element of this approach that is widely accepted is the acceptance of surprise which in turn implies that the idea of controlling ecosystems have to be abandoned (Holling, 1986; Walters, 1986; Gunderson *et al.*, 1995). In recent years adaptive management research has developed along two interlinked trajectories. On one side there is the line of research that was established by the scientists that first developed the approach such as Walters, Holling and Gunderson. On the other side, there is an approach that explicitly focuses on the linking problem, i.e., how social and ecological systems might be linked in order to be adaptive (Berkes and Folke, 1998). Since the late 1980s, Bayesian inference has become popular among fisheries scientists because of its ability to incorporate both uncertainty and prior knowledge and to provide information for risk analysis in evaluating alternative management strategies (Denns, 1996; McAllister and Pikitch, 1997).

Gerber *et al.* (2005) considered the role of monitoring the marine reserves to gain information needed for management decisions. In particular they used a decision theoretic framework to answer the question: how long should they monitor the recovery of an over-fished stock to determine the fraction of that stock to reserve? This exposed a natural tension between the cost (in terms of time and money) of additional monitoring and the benefit of more accurately parameterizing a population model for the stock, that in turn leads to a better decision about the optimal size for the reserve with respect to harvesting. They found that the optimal monitoring time frame is rarely more than 5 years. A higher economic discount rate decreased the optimal monitoring time frame, making the expected benefit of more certainly about parameters in the system negligible compared with the expected gain from earlier exploitation.

Feedback management is an effective strategy for taking into account unpredictable changes in the ecosystem, such as recruitment failure, as major causes of stock collapse. Tanaka (1982) proposed a simple feedback management strategy in which catch quotas are manipulated on the basis of the difference between present and target stock levels. Usually, a feedback policy is used to stabilize a state variable, while adaptive management attempts to learn about the system dynamics by varying a particular state. Both feedback and adaptive learning are important for the management of bio-resources whose dynamics are unstable and uncertain. Grafton and Kompas (2005) proposed a six step process : (i) Priorities and quantify management goals (ii) Socio-economic-ecological system appraisal (iii) Choose and apply ecological socio-economic criteria (iv) Determine reserve size, location, number and duration (v) Stakeholder and peer review (vi) Active learning, experimentation and evaluation, for establishing and adaptively managing reserves for fishery purposes.

Discussion

Most of the biological and economic references for fisheries that we have mentioned, deal with a single objective and the outputs are subsequently modified to account for objectives not specified in it. But the different objectives are not independent and need a frame work for making balanced decisions.

There is much interest in economic optimization of fishing strategies, but we need to remember that the economically optimal strategy is not necessarily the most desirable strategy for policy makers of fishers because other social, political and biological constraints may have more bearing on the management process.

Traditionally, the main goal in fisheries science was to find Maximum Sustainable Yield (MSY), the largest catches that can be taken over the long term without causing the population collapse. However, this is by no means the only objective of fishery management. The meaning of the word sustainable, which appears in the concept of Maximum Sustainable Yield (MSY) is important and needs to be explained. Harvesting a target species of fish affects not only that species but also disturbs whole ecosystems, which in turn can reduce target species. Although the primary goal of sustainable fisheries is to preserve the long term viability of target species, even harvest levels considered sustainable can impact marine ecosystems. If we can shift our way of thinking from MSY to ESY (ecological sustainable yield): the yield an ecosystem can sustain, we may reach to our objective.

Some difficulties are associated with taxation in fisheries. At the first, fishermen are always unanimously opposed to it. They would still receive zero rents, or at best inframarginal rents and the marginal fishermen would be eliminated entirely. The economic rents, now optimized, would accrue to the taxation authority. A second difficulty regards calculation of the optimal tax, which would require the management authority to know the operating cost structure as well as the biological characteristics of the fish population. Since real fish populations tend to fluctuate unpredictably, the optimal tax would have to be recalculated each fishing season.

As we mentioned that, fishermen inevitably oppose taxes, which they usually consider to be unfair, it might similarly be argued that the government, which represents the general public-the ultimate owners of the fishery resource-should oppose the free granting of quota rights to privileged individuals. A combined quota-tax system may be preferable (Clark, 1990). A practical compromise would first involve determining the total allowable catch in the usual way, based primarily on biological considerations. The total catch quota would then be allocated to individual vessels or sold to then at a price reflecting the desired tax.

To argue the case for marine reserves it is therefore necessary to show two things; first that they can work and second, that they are superior to other available management options. Available management options are here understood to refer to both technical and social availability. It is thus perfectively legitimate to argue as in Lauck *et al*. (1998) for the introduction of marine reserves not on the grounds that they are the best management method for a particular purpose but they are the best method that for socio-political reasons can be implemented. So it should be monitored.

Developing models that can illuminate the economic and ecological trade-offs involved in siting marine reserves are important as they can be used to reduce the set of contentious sites, transaction costs and feelings of disenchantment in the negotiation process.

The successful use of marine reserves require a case-by-case understanding of spatial structure of impacted fisheries, ecosystems and human communities. Marine reserves, together with other fishery management tools, can help achieve broad fishery and biodiversity objectives, but their use will require careful planning and evaluation. Mistakes will be made and without planning, monitoring and evaluation, we will not learn what worked, what did not and why. If marine reserves are implemented without case by case evaluation and appropriate monitoring programs, there is a risk of unfulfilled expectations, the creation of disincentives and a loss of credibility of what potentially is a valuable management tool.

It is important to realize that even when marine reserves of a certain size are optimal, their actual imposition may not hit the target. The problem the fisheries manager has in setting the correct marine reserves is qualitatively similar to the setting of the correct TAC or fisheries tax rate. The main difference is that the knowledge base for setting marine reserves is probably substantially weaker than that for those more traditional controls. In any case, it may easily happen that the actual imposition of marine reserves in a fishery where they are actually desirable is so imprecise that it actually makes matter worse rather than better. Under a system of ITQs, however, such mistakes may be reflected in the market values of permanent quotas which thus may serve as a guiding beam to the fisheries manager.

Restrictions on mesh size used in nets or traps are a common management measure. By increasing or decreasing mesh size, it is possible, to a limited degree, to increase or decrease the size of fish retained in the net. Control over the size at entry into the fishery can ensure that sufficient numbers of immature fish pass through the gear to protect the long-term productivity of the resource. It can be applied to all fisheries, but are generally used where fish are handled individually or in small groups.

Other methods, such as limited entry and nonallocated total catch quotas fail to address the basic economic problems of common- property resources and cannot be expected to result in a profitable fishing industry over the long run (Clark, 1990).

Fisher's behaviour has a critical influence on the likely success of fishery management measures and a failure to understand and manage fishers has contributed to many fisheries problems (Hilborn, 1985). For future fishery management to be effective it needs to be informed by a better understanding of the human-ecosystem interface, particularly with respect to fishers behaviour (McManus, 1996; Hanna, 2001).

One approach is to adopt adaptive management, to learn more about the effects of fishing and the potential of the fishery. This would consist of a series of experimental manipulation of the fishery. Also, fishery management is not a static process and feedback is needed to adjust management actions and ensure that management objectives are met.

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References

Ami, D., P. Cartigny and A. Rapaport, 2005. Can marine protected areas enhance both economic and biological situations? C. R. Biol., 328: 357-366.

Anderson, L.G. and D.R. Lee, 1986. Optimal governing instrument, operational level and enforcement in natural resource regulation: The case of fishery. Am. J. Agric. Econ., 68: 678-690.

Arnason, R., 2001. Property Rights as a Means of Economic Organization, In: Shotton, R. Ed., Use of Property Rights in Fisheries Management. Fao Fisheries Technical Paper 401/1. Rome: Food and Agriculture Organization of the United Nations.

Bagachwa, M.S.D., M.R.V. Hodd and T.L. Malyamkono, 1994. Fisheries Development in Tanzania. The Macmillan Press.

Berkes, F. and C. Floke, 1998. Linking Social and Ecological Systems, Management Practices and Social Mechanisms for Building Resilience, Cambridge University Press.

Beverton, R.J. and S.J. Holt, 1957. On the dynamics of exploited fish populations. Fisheries Investigations Series 2(19). London: Ministry of Agriculture, Fisheries and Food.

Brauer, F. and D.A. Sanchez, 2003. Periodic environments and periodic harvesting. Natl. Res. Model, 16: 233-244.

Brown, G. and J. Roughgarden, 1997. A metapopulation model with private property and a common pool. Ecol. Econ., 22: 65-71.

Casey, J.M. and R.A. Myers, 1998. Near extinction of a large, widely distributed fish. Science, 281: 690-692.

Chaudhuri, K.S., 1986. A bioeconomic model of harvesting: A multispecies fishery. Ecol. Model, 32: 267-278.

Chaudhuri, K.S. and T. Johnson, 1990. Bioeconomic dynamics of a fishery modeled as an S-system. Math. Biosci., 99: 231-249.

Chavez, C. and H. Salgado, 2005. Individual transferable quota markets under illegal fishing. Environ. Resource Econ., 31: 303-324.

Clark, C.W., 1979. Mathematical models in the economics of renewable resources. SIAM Rev., 21: 81-99.

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

Clark, C.W., 1990. Mathematical Bioeconomics: The Optimal Management of Renewable Resources. 2nd Edn., John Wiley and Sons, New York.

Clark, C.W., 1996. Marine reserves and precautionary management of fisheries. Ecol. Appl., 6: 369-370.

Conrad, J.M., 1999. The bioeconomics of marine sanctuaries. J. Biooecon., 1: 205-217.

DeMartini, E.E., 1993. Modeling the potential of fishery reserves for managing Pacific coral reef fishes. Fishery Bull., 91: 414-427.

Denns, B., 1996. Discussion: Should ecologists become Bayesians? Ecol. Appli., 6: 1095-1103.

Dong, L., L. Chen and L. Sun, 2006. Optimal harvesting policies for periodic Gompertz systems, Nonlinear Analysis. Real World Application, (In Press).

Doyen, L. and C. Bene, 2003. Sustainability of fisheries through marine reserves: A robust modeling analysis, J. Environ. Manage., 69: 1-13.

Dubey, B., P. Chandra and P. Sinha, 2002. A resource dependent fishery model with optimal harvesting policy. J. Biol. Sys., 10: 1-13.

Fan, M. and K. Wang, 1998. Optimal harvesting policy for single population with periodic coefficients. Math. Biosci., 152: 165-177.

FAO, 1994. Review of the state of world marine fishery resources. FAO Fisheries Technical *Paper* 335: 136.

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

Gallastegui, C., 1983. An economic analysis of sardine fishing in the Gulf of Valencia (Spain). J. Environ. Econ. Manage., 10: 138-150.

Ganguly, S. and K.S. Chaudhuri, 1995. Regulations of a single species fishery by taxation. Ecol. Modelling, 82: 51-60.

Gerber, L.R., M. Beger, M.A. McCarthy and H.P. Possingham, 2005. A theory for optimal monitoring marine reserves, Ecol. Lett., 8: 829-837.

Gislason, H., M. Sinclair, K. Sainsbury and R. O'Boyle, 2000. Symposium overview: incorporating ecosystem objectives within fisheries management. Ices J. Mar. Sci., 57: 468-475.

Gordon, H.S., 1954.The economic theory of a common property resource: The fishery. J. Political Econ., 62: 124-142.

Grafton, R.Q., T. Kompas and D. Lindenmayer, 2005. Marine reserves with ecological uncertainty. Bull. Math. Biol., 67: 957-971.

Grafton, R.Q. and T. Kompas, 2005. Uncertainty and the active adaptive management of marine reserves. Marine Policy, 29: 471-479.

Guenette, S. and T.J. Pitcher, 1999. An age-structured model showing the benefits of marine reserves in controlling overexploitation. Fish Res., 39: 295-303.

Gulland, J.A., 1983. Fish Stock Assessment; A Manual of Basic Methods. John Wiley and Sons, New York.

Gunderson, L.H., C.S. Holling and S.S. Light, 1995. Barriers and Bridges to the Renewal of Ecosystems and Institutions. New York, NY: Columbia University Press.

Hanna, S.S., 2001. Managing the human ecological interface: Marine resources as example and laboratory. Ecosystems, 4: 736-741.

Hannesson, R., 1982. Optimal harvesting of ecologically interdependent fish species. J. Environ. Econ. Manage., 10: 329-345.

Hannesson, R., 1989. Optimum fishing effort and economic rent: A case study of cyprus, FAO Fisheries Technical Paper Number 299, Rome.

Hannesson, R., 1998. Marine reserves: What would they accomplish? Marine Resource Econ., 13: 159-170.

Hannesson, R., 2002. The economics of marine reserves. Natural Resource Modeling, 15: 273-290.

Hastings, A. and L.W. Botsford, 1999. Equivalence in yield from marine reserves and traditional fisheries management. Science, 284: 1537-1538.

Hilborn, R., 1985. Fleet dynamics and individual variation: Why some people catch more fish than others. Can. J. Fish. Aquat. Sci., 42: 2-13.

Hilborn, R., 2002. The dark side of reference points. Bull. Mar. Sci., 70: 403-408.

Hilborn, R. and M. Mangel, 1997. The Ecological Detective: Confronting Models with Data. Princeton University Press, NY, USA, pp: 315.

Holland, D.S. and R.J. Brazee, 1996. Marine reserves for fisheries management. Marine Resource Econ., 11: 157-171.

Hutchings, J.A. 2000a. Numerical assessment in the front seat, ecology and evolution in the back seat: Time to change drives in fisheries and aquatic science? Mar. Ecol. Prog. Ser., 208: 299-313.

Hutchings, J.A., 2000b. Collapse and recovery of marine fishes. Nature, 406: 882-885.

Holling, C.S., 1978. Adaptive Environmental Assessment and Management, NY, USA. John Wiley and Sons.

Holling, C.S., 1986. The Resilience of Terrestrial Ecosystems: Local Surprise and Global Change. In: Sustainable Development of the Biosphere. Ed. Clark, W.C. and R.E. Munn, Cambridge University Press, Cambridge, UK., pp: 292-317.

Hormons, F. and J. Wilen, 1997. A model of regulated open access resource use. J. Environ. Econ. Manage., 32: 1-21.

Imeson, R.J., J. Van Den Bergh and J. Hoekstra, 2002. Integrated models of fisheries management and policy. Environ. Modeling Assessment, 7: 259-271.

Kar, T.K. and K.S. Chaudhuri, 2003. Regulation of a prey-predator fisgery by taxation: A dynamic reaction model. J. Biol. Sys., 11: 173-187.

Kar, T.K., 2004. Management of a fishery based on continuous fishing effort. Nonlinear Analysis: Real World Application, 5: 629-644.

Kar, T.K., 2005. Stability and optimal harvesting of a prey-predator model with stage structure for predator. Appli. Math., 32: 279-291.

Kar, T.K. and K.S. Chaudhuri, 2004. Harvesting in a two prey one predator fishery : A bioeconomic model. ANZIAM J., 45: 443-456.

Kar, T.K. and H. Matsuda, 2006a. Modelling and analysis of marine reserve creation, J. Fish Aqua. Sci., 1: 17-31.

Kar, T.K. and H.M. Matsuda, 2006b. Controllability of a harvested prey-predator system with time delay. J. Biol. Sys., 14: 1-12.

Kar, T.K., U.K. Pahari and K.S. Chaudhuri, 2004. Management of a single species fishery with stage structure. Intl. J. Math. Educ. Sci. Technol., 35: 403-414.

Katsukawa, T., 2004. A numerical investigation of the optimal control rule for decision making in fisheries management. Fish. Sci., 70: 123-131.

Kellog, R.L., J.E. Easley and T. Johnson, 1988. Optimal timing of harvest for the North Carolina Banj Scallop Fishery. Am. J. Agric. Econ., 70: 50-62.

Krishna, S.V., P.D.N. Srinivasu and B. Kaymakcalan, 1998. Conservation of an ecosystem through optimal taxation. Bull. Math. Biol., 60: 569-584.

Law, R., 2000. Fishing, selection and phenotype evolution. ICES J. Mar. Sci., 57: 659-668.

Lauck, T., C.W. Clark, M. Mangel and G.R. Munro, 1998. Implementing the precautionary principle in fisheries management through marine reserves. Ecol. Appli., 8: s72-s78.

Mangel, M., 2000. Trade-offs between fish habitat and fishing mortality and the role of reserves. Bull. Marine Sci., 66: 663-674.

Man, A., R. Law and N.V.C. Polunin, 1995. Role of marine reserves in recruitment to reef fisheries: a meta-population model. Biol. Conserv., 71: 197-204.

Matsuda, H. and T. Katsukawa, 2002. Fisheries management based on ecosystem dynamics and feedback control. Fish. Oceanogr., 11: 366-370.

Matsuda, H. and K. Nishimori, 2002. A size structured model for a stock recovery program for an exploited endemic fisheries resource. Fish. Res., 1468: 1-14.

Matsuda, H. and P. Abrams, 2006. Maximal yields from multi-species fisheries systems: Rules for systems with multiple trophic levels. Ecol. Appli., 16: 225-237.

Matsuda, H., A. Yamauchi, Y. Matsumiya and T. Yamakawa, 1999. Reproductive value, harvest value, impact multiplier as indicators for maximum sustainable fisheries. Environ. Econ. Pol. St., 2: 129-146.

McManus, J.W., 1996. Social and Economic Aspects of Reef Fisheries and Their Management. In: Reef Fisheries, Eds. Polunin, N.V.C. and C.M. Roberts, London, UK: Chapman and Hall, pp: 249-281.

McAllister, M.K. and E.K. Pikitch, 1997. A bayesian approach to choosing a design for surveying fishery resources: Application to the eastern Bering Sea trawl survey. Can. J. Fish. Aquat. Sci., 54: 301-311.

Mesterton Gibbons, M.A., 1996. Technique for finding optimal two-species harvesting policies. Ecol. Model, 92: 235-244.

Munro, G.R. and A.D. Scott, 1985. The Economics of Fisheries Management, in Kneese, A.V. and J.L. Sweeney (Eds.), Handbook of Natural Resource and Energy Economics. North Holland: Elsevier Science Publishers, pp: 623-676.

Parma, A., 1990. Optimal harvesting of fish populations with nonstationary stock-recruitment relationships. Natl. Resource Model. 4: 39-76.

Pitcher, T.J., 1998. A cover story: Fisheries may drive stocks to extinction. Rev. Fish. Biol. Fish, 8: 367-370.

Polacheck, T., 1990. Year around closed areas as a management tool. Natl. Res. Model., 4: 327-354.

Pradhan, T. and K.S. Chaudhuri, 1998. Bioeconomic modeling of a single species fishery with Gompertz law of growth. J. Biol. Sys., 6: 393-409.

Pradhan, T. and K.S. Chaudhuri, 1999. A dynamic reaction model of a two species fishery with taxation as a control instrument: A capital theoretic analysis. Ecol. Model, 121: 1-16.

Punt, A.E., 2000. Extinction of marine renewable resources: A demographic analysis, Popul. Ecol., 42: 19-27.

Reed, W.J., 1979. Optimal escapement levels in stochastic and deterministic harvesting models. J. Environ. Econ. Manag., 6: 350-363.

Roberts C.M., G. Branch, R.H. Bustamante, J.C. Castilla and J. Dugan *et al*., 2003. Application of ecological criteria in selecting marine reserves and developing reserve networks. Ecol. Appli., 13: s215-s228.

Sadovy, Y., 2001. The threat of fishing to highly fecund fishes. J. Fish. Biol., 59: 90-108.

Sanchirico, J.N. and J.E. Wilen, 1999. Bioeconomics of spatial exploitation in a patchy environment. J. Environ. Econ. Manage., 37: 129-150.

Sanchirico, J.N. and J.E. Wilen, 2001. A bioeconomic model of marine reserve creation. J. Environ. Econ. Manage., 42: 257-276.

Schaefer, M.B., 1954. Some aspects of the dynamic of population important to the management of the commercial marine fisheries. Inter-Am. Trop. Tuna Commission Bull., pp: 27-56.

Smith, M.D. and J.E. Wilen, 2003. Economic impacts of marine reserves: the importance of spatial behavior. J. Environ. Econ. Manage., 46: 183-206.

Song, X. and L. Chen, 2001. Optimal harvesting and stability for a two species competitive system with stage structure. Math. Biosci., 170: 173-186.

Song, X. and L. Chen, 2002. Optimal harvesting and stability for a predator-prey system with stage-structure. Acta Mathematicae Applicatae Sinica, English Series, 18: 423-430.

Strobele, W.J. and H. Wacker, 1995. The economics of harvesting predator-prey systems. J. Econ., 61: 65-81.

Sumaila, U.R., 1998. Protected marine reserves as fisheries management tools. A bioeconomic analysis. Fish. Res., 37: 287-296.

Sutinen, J.G. and P. Anderson, 1985. The economics of fisheries law enforcement, Land. Econ., 61: 387-397.

Tanaka, S., 1982. The management of a stock fishery system by manipulating the catch quota based on the difference between present and target stock level. Bull. Japan Soc. Sci. Fish., 48: 1725-1729.

Townsend, R.E., 1986. A. critique of models of the American lobster fisheries. J. Environ. Econ. Manage., 13: 277-291.

Wacker, H., 1999. Optimal harvesting of mutualistic ecological systems. Resource and Energy Econ., 21: 89-102.

Walters, C.J. and R. Hilborn, 1976. Adaptive control of fishing systems. J. Fish Res. Bd. Can., 33: 145-159.

Walters, C.J., 1986. Adaptive Management of Renewable Resources. NY, USA: McMillan.

Walters, C.J., 1997. Challenges in adaptive management of riparian and coastal ecosystems. Conservation Ecology [online] 1(2):1. URL: http://www.consecol.org/vol1/iss2/art1.

Weninger, Q.R. and R.E. Just, 1997. An analysis of transition from limited entry to transferable quota: Non-marshallian principles for fisheries management. Natural Resource Modelling, 10: 33-45.

Zhang, X., Z. Shuai and K. Wang, 2003. Optimal impulsive harvesting policy for single population. Nonlinear Anal. Real. World Application, 4: 639-651.