INCORPORATING HABITAT DYNAMICS INTO BIOECONOMIC MODEL OF FISHERY. APPLICATION TO ARTIFICIAL REEFS

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ABSTRACT

In this paper the emphasis is put on an important aspect of renewable resource use that was disregarded until now. It is the evolution of environmental carrying capacity which is traditionally interpreted as a maximal population level that can be supported by the environment (or by habitats of which it consists). Hence we adapt the Gordon-Schaefer model with constant carrying capacity by incorporating time-dependent carrying capacity that determines the state of habitats. They are subject to some biological processes (habitat rehabilitation) as well as to human aggressions (in particular habitat degradation due to fishing). Based on the developed model, we reassess the recommendations considered as a benchmark for resource managers until recently. Under simple hypotheses on the form of habitat (carrying capacity) dynamics, the current study has shown the importance of the latter for the design of management tools. When dynamic patterns of habitats are not taken into account, fishery recommendations based on Gordon-Schaefer model can be aberrant and lead to the collapse of the fishery. The presented model allows not only to enrich the design of management tools but also to assess the performance of artificial reefs, a promising ecosystem-based tool widely used in some coastal areas. The economic benefits of artificial reefs are still not well studied and represent a challenge to take up. Since artificial reefs are conceived as replacement for natural habitats, they assume the same role as these latter. Therefore the structure of our model seems appropriate to evaluate this particular management tool.

Keywords: Gordon-Schaefer model, Marine habitats, Artificial reefs

INTRODUCTION

In order to preserve the halieutic resource, numerous management tools were applied such as access limitations, quotas, taxes or subsidies. Over the years, it has become obvious that those tools have not succeeded in maintaining the marine resources at sustainable levels. The principal management mechanism that is employed to regulate a fishery is to restrain the quantities of fish that can be landed through implementing annual total allowable catches (TACs) for the target species. However, TAC regime is not always sufficient to conserve the resource because of the pressure on non-target components of marine ecosystems [16]. As a result, the majority of marine resources are presently almost or completely overexploited [3,11]. The successful management cannot be reached without clear understanding of biological processes at an ecosystem level. In this vein many recent studies promote new vision for fisheries management according to which ecosystem attributes must be integrated into management. Such approach to resource regulation is called ecosystem-based management [14,15]. Due to ecosystem concerns fisheries management tools like marine protected areas, (for short MPAs, [10,18,19,20]) and artificial reefs (for short ARs, [12,13]) were pointed out.

The extensive research on the biological and economic effects of MPAs led to the design of spatially explicit bioeconomic model of fishery [18] where fish populations can migrate from one area to another. Modelling a spatially distributed resource was a step further in integrating the motivations behind ecosystem-based management that cannot be efficiently conceived without considering spatial dimension.

In the same manner artificial reefs policy has arised from an important ecosystem concern such as fish habitat degradation. A habitat is a specific area or environment in which a plant or animal lives. It provides all the basic requirements for survival. Soft sandy to muddy bottom or hard (rocky, coral) shore are some examples of marine habitats. Habitat degradation is a major threat to species worldwide [1,17]. Indeed, marine areas have endured high levels of habitat destruction. About one-fifth of marine coastal areas have been highly modified by humans [2]. Coral reefs that support high diversity of fishes continue to decline. It threatens fish biodiversity and MPAs are not always sufficient to ensure its survival in degrading environments [9].

To our knowledge, there is still no theoretical results regarding the management of fish habitats. In this context the recommendations resulting from the studies of Schaefer [21] and Gordon [5] and widely used in fisheries regulation need to be adapted. Their model is the foundation for fisheries economics literature and referred to as the Gordon-

Schaefer model (for short, the G-S model). It provides recommendations concerning the sustainable level of fish population and effort level such as MSY (Maximum Sustainable Yield), which maximizes sustainable yield, or MEY (Maximum Economic Yield), which maximizes sustainable economic rents. Nevertheless, there was an attempt to integrate the habitats into the analysis of optimal fisheries management [7]. Holland and Schnier [7] have studied the possibility to implement an individual habitat quota system to achieve habitat conservation via economic incentives. They adapted the G-S model by integrating habitat stock endowed with its own dynamics. By simulating the model they investigate the conditions in which individual habitat quota regime is more cost-effective than MPA. However, their model does not establish any connexion between fish dynamics and the evolution of habitats.

In this paper we propose another extension of the G-S model by incorporating dynamics of the carrying capacity of a given marine area for the target species. The carrying capacity is traditionally interpreted as a maximal population level that can be supported by a marine area. It is one of the determinants of fish stock dynamics. We assume that the evolution of area's carrying capacity results from that of marine habitats present in the area. Through some experimental treatments, Griffen and Drake [6] have found that the carrying capacity is influenced by habitat size and quality and is correlated with extinction time: larger habitats support populations with higher carrying capacities; higher quality habitats support populations with higher carrying capacities.

The carrying capacity is hence entirely subject to natural (or man-made) habitat rehabilitation processes and habitat alteration induced by fishing. Natural habitat rehabilitation includes, amongst other recovery processes (for instance, recovery from physical impacts), the growth of plants and animal populations that colonized the habitat and which are indispensable for the fish reproduction and survival. On the other hand, alteration of habitat refers to a change in the structure or function of habitat, making it potentially unsuitable for the organism to live in. Habitat degradation takes two forms: decreased habitat size because of habitat loss or fragmentation, and decreased habitat quality through loss of resources, pollution or other forms of habitat alteration. Some fishing techniques may cause habitat destruction (dynamite fishing, cyanide fishing, or bottom trawling) while others have a negligeable habitat impact (for example, pelagic longlines or hook and line). Fishing impacts extends from the extraction of a species which distorts community composition and diversity to reduction of habitat complexity by direct physical impacts of fishing gear [8].

In the next section we present our model and the assumptions. Then model functions are specified and its equilibrium behaviour is studied. In the section 4 problem of optimal management is addressed. Finally, we illustrate main results by giving a numerical example.

THE MODEL

In this section the G-S model is presented then the model is extended so that habitat concerns could be taken into account in the analysis of optimal fisheries management.

Following Schaefer [21], the biomass x of a given fish species obeys the following equation:

$$\dot{x} = F(x) - H(x,E) \qquad \text{(Eq. 1)}$$

where $F(x)$ is the natural rate of growth of the fish biomass (it is also called surplus production) while $H(x,E)$ is the rate of harvest.

Since fishing has a considerable effect on the habitat and thus on the carrying capacity K of the concerned area, we modify the G-S model by considering K as a variable:

$$\dot{K} = D(K) - G(E,K) \qquad \text{(Eq. 2)}$$

where $D(K)$ is a growth function of carrying capacity driven by habitat rehabilitation and $G(E,K)$ describes the process of habitat degradation expressed by decreased carrying capacity.

Note that marine area being geometrically limited, it cannot support an infinite quantity of fish and thus its carrying capacity is bounded by some upper limit $K_{\max}$.

As in Schaefer [21], we assume that $F(x,K)$ follows logistic law:

$$F(x,K) = rx\left(1 - \frac{x}{K}\right) \qquad \text{(Eq. 3)}$$

with r intrinsic growth rate and K area's carrying capacity for the considered fish species.

However, the harvest function is slightly modified compared to the standard assumption on its form (see [4])

$$H(x,E,K) = qE\frac{x}{K} \quad \text{(Eq. 4)}$$

with q catchability coefficient and E fishing effort.
(Eq. 4) assumes not only that the harvests per unit of effort are proportional to the fish stock but also that for a given level of fish stock, with higher carrying capacity, it is more difficult to harvest the fish due to a stronger fish dispersal (larger habitats provide more places where the fish can hide and feed).

MODEL SPECIFICATION AND EQUILIBRIUM ANALYSIS

In this section we specify the functions of the model (Eq. 3)-(Eq. 4) and analyze its steady-state behaviour.
If we assume that D obeys logistic law and G has a form similar to that of harvest function H, then

$$\dot{x} = rx(1 - x/K) - qEx/K \quad \text{(Eq. 7)}$$

$$\dot{K} = \tau K(1 - K/K_{\max}) - \gamma EK \quad \text{(Eq. 8)}$$

where τ is the growth rate of K driven by habitat recovery (or "growth"), γ is the loss rate of K due to habitat alteration caused by aggressive fishing and $K_{\max}$ is the area's maximal possible carrying capacity.

Main features of the model

Let us state the main characteristics of the model (Eq. 7)-(Eq. 8).
1) Properties of the fish growth rate $F(x,K)$:

(1a) $\dfrac{\partial F}{\partial x}$ is positive for smaller values of x and negative for larger values;

This condition expresses the idea that increase of a given fish species at every moment of time is realized only up to a certain degree, depending on the unutilized opportunity for growth at this moment. As the number of individuals increases, the unutilized opportunity for the further growth decreases, until finally the greatest possible or saturating population in the given conditions is reached.

(1b) $\dfrac{\partial F}{\partial K} > 0$ and (1c) $\dfrac{\partial^2 F}{\partial K^2} < 0$;

According to (1b), the fish biomass grows faster in a marine area with larger carrying capacity. It means that higher availability of habitats encourages fish reproduction. (1c) indicates that the contribution of K in fish growth rate decreases as K increases.
2) Properties of the harvest function $H(x,K,E)$:

(2a) $\dfrac{\partial H}{\partial x} > 0$, (2b) $\dfrac{\partial H}{\partial E} > 0$ and (2c) $\dfrac{\partial H}{\partial K} < 0$;

If we interpret H as a production function, then (2a) and (2b) are usual conditions on the "factors of production" (here E and x): the output increases with increasing inputs E and x. (2c) can be interpreted as follows: higher carrying capacity leads to a higher dispersal of fishes which is why it is more difficult to catch them.
We interpret the assumptions regarding carrying capacity from the perspective of habitats because, as noted previously, they are supposed to entirely determine the behaviour of K.
3) Properties of the growth rate $D(K)$ of the carrying capacity :

(3a) $\dfrac{\partial D}{\partial K}$ is positive for smaller values of K and negative for larger values;

Since habitat recovery corresponds to the growth of plant and animal communities, on which the fish species in question is ecologically dependent, it is relevant to adopt the same assumptions as for the fish growth F. There is a certain level of those plant and animal populations after which their growth rate decreases due to environmental saturation (for instance, driven by geometrical limits).

4) Properties of the loss rate $G(K,E)$ of area's carrying capacity:

(4a) $\frac{\partial G}{\partial K} > 0$ and (4b) $\frac{\partial G}{\partial E} > 0$;

For G we adopt equivalent assumptions as for the harvest function H. (4a) means that the larger is the carrying capacity of a marine area (supposing that faune and flore of habitats are more developped), more plants and animals representing food for fish are exposed to fishing gears which leads to higher losses in K. In the same vein, (4b) states that the higher is the fishing pressure E on habitats, more serious is the damage inflicted to them followed by losses in K.

Equilibrium and stability

We analyze the equilibrium of the model (Eq. 7)-(Eq. 8) considering that fishing effort E is a parameter. The steady states of fish stock x and carrying capacity K for a constant effort E are $x_1^* = 0,\ \ x_2^* = K^* - \frac{q}{r}E$ and $K_1^* = 0,\ \ K_2^* = K_{\max}(1 - \frac{\gamma}{\tau}E)$. However K_1^* is not acceptable because of the form of the harvest function H represented by the expression (Eq. 6). We are interested in the positive equilibrium point (x_2^*, K_2^*).

The linearised system of equations (Eq. 7)-(Eq. 8) at (x_2^*, K_2^*) is

$$V(x_2^*, K_2^*) = \begin{pmatrix} qE / K_2^* - r & r - qE / K_2^* \\ 0 & \gamma E - \tau \end{pmatrix}.$$

Due to the condition of positivity of x_2^* and K_2^*, we obtain negatives eigen values $qE / K_2^* - r < 0$ and $\gamma E - \tau < 0$. As a result, (x_2^*, K_2^*) is asymptotically stable.

The behaviour of the model at a steady state depends on the fishing effort E. If no fishing takes place, i.e. $E = 0$, for non zero initial carrying capacity and fish stock, both attain their maximum, $K^* = K_{\max},\ x^* = K_{\max}$. The fish stock and carrying capacity are positive at a steady state if the effort $E < K_{\max} / (\frac{\gamma K_{\max}}{\tau} + \frac{q}{r})$.

As we can see the level of fish stock x at equilibrium depends on the area's carrying capacity K. It increases with K and can collapse if the effort E is such that $E = \frac{rK}{q}$. Thus for higher K higher effort can be applied without leading to a total collapse of the fish populations. Conversely, for lower K lower effort can result in fish collapse. Furthermore, in addition to the usual constraint of fish stock positivity $E < \frac{rK}{q}$, the fishing effort must be sufficiently low to keep the carrying capacity above zero, i.e. $E < \frac{\tau}{\gamma}$, in order to avoid total dispersal of fish.

This first analysis demonstrates that incorporating the dynamics of carrying capacity enriches the analysis. According to the equilibrium behavior of the model, it is possible for the fish stock to collapse because of the destruction of habitats. Thus the proposed model makes biological and economic motivations behind habitat conservation transparent. The resource cannot be preserved without protecting the habitats.

Biological and economic overfishing

Let us now explore the bionomic equilibrium where the economic rent R represented by the following function dissipates at a steady state:

$$R(x,K,E) = pqEx/K - cE \qquad \text{(Eq. 9)}$$

where p is a constant price of fish and c is a constant cost per unit of effort. The price p is exogenous.

Following Gordon [5], under open access the fishing effort will increase while the rent is still positive. If the rent is negative, some fishing units will leave the fishery until the rent stabilizes at zero.

The bionomic equilibium is attained for

$$x_\infty = \frac{cK_\infty}{pq},\ K_\infty = K_{\max}/\left(1 + \frac{r\gamma K_{\max}}{\tau q}(1 - \frac{c}{pq})\right),\ E_\infty = K_M\left(1 - \frac{c}{pq}\right)/\left(\frac{q}{r} + \frac{\gamma K_M}{\tau}\left(1 - \frac{c}{pq}\right)\right).$$

As in the G-S model the effort E_∞ leading to the rent dissipation depends on the economic parameters of the fishery p, c and q as well as on the fish growth rate r. However, it also depends on the parameters τ and γ describing the dynamics of carrying capacity. The parameters c and γ are negatively related to E_∞ whereas p, r, τ and $K_{\max}$ are positively correlated to it. The catchability coefficient q depends on the ratio c/p. Thus for higher rate of habitat rehabilitation (implying higher τ) higher effort E can be supported by the fishery without dissipating economic rent. Similarly, higher habitat degradation rate leads to lower E_∞. Further, the rent dissipates for the level of effort that is lower than predicted by the G-S model.

Bionomic equilibrium describes the situation of economic overfishing where the resource, capable of producing positive economic rent, instead is producing zero rent because of excessive level of effort.

Another type of overexploitation is referred to as the biological overfishing that occurs if the level of fish stock is lower than MSY. The concept of MSY assumes that at any given level of fish stock x below K, a surplus production $F(x)$ exists that can be harvested in perpetuity without altering the stock level [4]. MSY is achieved at the population level where surplus production is greatest.

The sustained harvests $H(x_2^*, K_2^*, E)$ are maximized for

$$x_{MSY} = K_{MSY} - \frac{q}{r}E_{MSY},$$

$$K_{MSY} = K_{\max}\sqrt{q/\left(\frac{r\gamma K_{\max}}{\tau} + q\right)},$$

$$E_{MSY} = \frac{\tau}{\gamma}\left(1 - \sqrt{q/\left(\frac{r\gamma K_{\max}}{\tau} + q\right)}\right).$$

Similarly to G-S model the effort that maximizes the sustained harvests depends only on resource and habitat specific parameters. Note also that the level of carrying capacity at which MSY is attained is not its maximum $K_{\max}$. This result is not suprising because K_{MSY} must trade off the profit that can be gained from increased fish stock (postitive impact of K on the harvest function H) and the losses due to the fish dispersal (negative impact of K on the harvest function). On the other hand, the MSY recommendation calculated on the basis of the G-S model is to exert effort $E = \frac{rK_0}{2q}$ where K_0 is the level of carrying capacity at the moment of the assessment of the state of habitats. Since it does not take into account the evolution of habitats, i.e. the parameter K_0 is considered as constant, no recommendations are given regarding the carrying capacity of habitats. Thus if K_0 is lower than K_{MSY}, then the MSY is not achieved and the resource faces biological overexploitation. Conversely, if K_0 is higher than K_{MSY} the fish stock stabilizes at a level higher than x_{MSY}. Even if biological overfishing does not occur, the resource could be economically underexploited.

OPTIMAL FISHERY MANAGEMENT

Consider a regulator that seeks to maximize the total discounted net revenues derived from exploitation of the resource by controlling the fishing effort E:

$$\underset{0\le E\le E_M}{Max}\ J\{E\} = \int_0^\infty e^{-\delta t} R(x, E, K)dt \qquad \text{(Eq. 10)}$$

under constraints (Eq. 3)-(Eq. 4) with initial conditions $x(0) = x_0, K(0) = K_0$.

The objective of the regulator can be interpreted in terms of capital asset. He expects the asset to earn dividends. If he is not satisfied with the rate of return, the regulator would attempt to dispose of the asset. Here two capital assets - fish stock and carrying capacity - can be distinguished where the latter influences the former (but the possibility of the inverse is not taken into account in our model). The optimal fishery management consists in an optimal investment strategy in those assets as they determine the profitability of the fishery. In this section we explore the above optimization problem for the general structure of the model.

In order to solve this maximization problem we build its Hamiltonian:

$$\mathsf{H}(x, K, t, E, \lambda, \mu) = R(x, K, E) + \lambda(F(x, K) - H(x, K, E)) + \mu(D(K) - G(K, E)), \qquad \text{(Eq. 11)}$$

where $\lambda(t)$ is the shadow price of a fish in the sea and $\mu(t)$ is the shadow price of the carrying capacity of the marine area.

Three terms on the right side of the expression (Eq. 11) are value flows: the first depicts the flow of accumulated dividends to the objective functional J; the second can be seen as the investment flow in the fish stock x; the last, new, term is the flow of investment in the environmental carrying capacity K. Thus the Hamiltonian H represents the total rate of increase of dividends and the two capital assets and the optimal control $E(t)$ must maximize the rate of increase of total assets.

Given the linear form of the harvest and cost functions, the Hamiltonian (11) depends linearly on E with coefficient

$$\sigma = p\frac{\partial H}{\partial E} - \lambda\frac{\partial H}{\partial E} - \mu\frac{\partial G}{\partial E}, \qquad \text{(Eq. 12)}$$

referred to as the switching function. In this case three solutions for E are possible: either the extremes 0 or E_M, or an interior solution E^*. One must fish as much as possible when σ is positive, i.e. the shadow prices λ and μ are sufficiently low. When those are sufficiently high (σ is negative), one must not fish at all. Finally, if the switching function is nul, then the control E must be set at its "singular value" E^*. With respect to this, by the Pontryagin conditions, we have:

$$\dot{\lambda} = \delta\lambda - \frac{\partial \mathsf{H}}{\partial x} = \delta\lambda - p\frac{\partial H}{\partial x} - \lambda\left(\frac{\partial F}{\partial x} - \frac{\partial H}{\partial x}\right), \qquad \text{(Eq. 13)}$$

$$\dot{\mu} = \delta\mu - \frac{\partial \mathsf{H}}{\partial K} = \delta\mu - p\frac{\partial H}{\partial K} - \lambda\left(\frac{\partial F}{\partial K} - \frac{\partial H}{\partial K}\right) - \mu\left(\frac{\partial D}{\partial K} - \frac{\partial J}{\partial K}\right). \qquad \text{(Eq. 14)}$$

Let us rewrite the condition (Eq. 12):

$$(p - \lambda)\frac{\partial H}{\partial E} = c + \mu\frac{\partial G}{\partial E}. \qquad \text{(Eq. 15)}$$

This equation states that the last unit of effort is such that the net value of the marginal product (its market price if caught minus its shadow price if uncaught) equals marginal user cost. The marginal user cost consists of the marginal cost of effort and the cost due to damaging marine habitats (shadow value of "removed" carrying capacity).

Write (Eq. 13) and (Eq. 14) as:

$$(p - \lambda)\frac{\partial H}{\partial x} + \dot{\lambda} = \delta\lambda - \lambda\frac{\partial F}{\partial x}; \qquad \text{(Eq. 16)}$$

$$(p - \lambda)\frac{\partial H}{\partial K} + \dot{\mu} = \delta\mu - \lambda\frac{\partial F}{\partial K} - \mu\left(\frac{\partial D}{\partial K} - \frac{\partial G}{\partial K}\right). \qquad \text{(Eq. 17)}$$

The left-hand side of the expression (Eq. 16) is the marginal net payoff from an uncaught fish i.e. the value of the marginal product of a fish in the sea plus gains from fish capital. The right-hand side is the marginal net cost of an uncaught fish i.e. the "financial cost" of an uncaught fish minus (plus) the value of "appreciation" (depreciation) at the "biological own rate of interest".

In the same manner, the left-hand side of (Eq. 17) is recognized as the marginal net payoff from the carrying capacity not impacted by fishing. The right-hand side is the marginal net cost. There are four terms describing user costs:

"financial cost" of not "removing" the carrying capacity;

plus (minus) value of depreciation (appreciation) of fish capital;

plus (minus) value of depreciation (appreciation) of carrying capacity capital;

plus (minus) value of marginal increase (decrease) of carrying capacity loss rate induced by fishing.

Since it is difficult to find a solution that satisfies the above conditions, we focus on finding equilibrium solution. Hence we equalize state and costate equations to zero and study the interior equilibrium. With respect to this and in view of model specification (Eq. 7)-(Eq. 8), the necessary conditions can be rewritten as:

$$\dot{x} = 0 \Leftrightarrow x = K - \frac{qE}{r}; \qquad \text{(Eq. 27)}$$

$$\dot{K} = 0 \Leftrightarrow K = K_{\max}\left(1 - \frac{\gamma E}{\tau}\right); \qquad \text{(Eq. 28)}$$

$$\dot{\lambda} = 0 \Leftrightarrow \lambda = \frac{pqE/K}{\delta + f}; \qquad \text{(Eq. 29)}$$

$$\dot{\mu} = 0 \Leftrightarrow \mu = \frac{\lambda x}{K}\left(\frac{r - \delta - f}{\delta + g}\right); \qquad \text{(Eq. 30)}$$

$$\frac{pqx}{K} - c - \frac{\lambda qx}{K} - \mu\gamma K = 0, \qquad \text{(Eq. 31)}$$

where $f = -\left(F_x - \frac{F}{x}\right) = \frac{rx}{K}$ and $g = -\left(D_K - \frac{D}{K}\right) = \frac{\tau K}{K_{\max}}$.

By virtue of (Eq. 29) and (Eq. 30), we rewrite (31):

$$x\left(1 - \frac{qE/K}{\delta + f} - \frac{\gamma E(r - \delta - f)}{(\delta + f)(\delta + g)}\right) = \frac{cK}{pq}. \qquad \text{(Eq. 32)}$$

After some substitutions we have:

$$x^* = K_{\max} - \left(\frac{q}{r} + \frac{\gamma K_{\max}}{\tau}\right)E^*, \qquad \text{(Eq. 33)}$$

$$K^* = K_{\max}\left(1 - \frac{\gamma E^*}{\tau}\right), \qquad \text{(Eq. 34)}$$

$$\lambda^* = pqE^* / \left(K_{\max}(\delta + r) - \left(q - \frac{\gamma K_{\max}}{\tau}(\delta + r)\right)E^*\right), \qquad \text{(Eq. 35)}$$

$$\mu^* = \frac{\lambda^* x^*}{K^*}\left(\frac{qE^*/K^* - \delta}{\delta + \tau - \gamma E^*}\right), \qquad \text{(Eq. 36)}$$

where E^* is a root of the following polynomial of degree 3:

$$k_1 E^3 + k_2 E^2 + k_3 E + k_4 = 0, \qquad \text{(Eq. 37)}$$

with

$$k_1 = -\gamma(r\gamma K_{\max} + \tau q)^2 - r\gamma K_{\max}\frac{c}{pq}(\delta\gamma K_{\max} + r\gamma K_{\max} + \tau q)];$$

$$k_2 = (r\gamma K_{\max} + \tau q)(\delta^2 \gamma K_{\max} + \tau(3r\gamma K_{\max} + 2\tau q) + \delta(2\tau q + \gamma K_{\max}(r+\tau))) -$$
$$- r\gamma K_{\max} \frac{c}{pq}(\delta^2 \gamma K_{\max} + \tau(3r\gamma K_{\max} + 2\tau q) + \delta(\tau q + \gamma K_{\max}(r+3\tau)));$$
$$k_3 = \tau K_{\max}[r\frac{c}{pq}(2\delta^2 \gamma K_{\max} + \tau(3r\gamma K_{\max} + \tau q) + \delta(2r\gamma K_{\max} + 3\tau\gamma K_{\max} + \tau q)) -$$
$$-(3r\tau(r\gamma K_{\max} + \tau q) + \delta^2(2r\gamma K_{\max} + \tau q) + \delta(2r\gamma K_{\max}(r+\tau) + \tau q(3r+\tau)))];$$
$$k_4 = r\tau^2 K_{\max}^2(\delta + r)(\delta + \tau)\left(1 - \frac{c}{pq}\right).$$

The term k_4 is positive due to the obvious constraint of nonnegative sustainable economic rent that is satified for $\frac{c}{pq} < 1$. Thereby, for any set of parameters such that $k_1 < 0$, we can guarantee that this polynomial has at least one positive root. Imposing negativity on k_1 means constraining the ratio $\frac{c}{pq}$ by some upper bound i.e.

$$\frac{c}{pq} < \frac{(r\gamma K_{\max} + \tau q)^2}{r\gamma K_{\max}(\delta\gamma K_{\max} + r\gamma K_{\max} + \tau q)}.$$

It can be checked that the steady state $(x^*, K^*, \lambda^*, \mu^*)$ is a saddle point. Therefore, by the Hartman-Grobman and the stable manifold theorems, for (x_0, K_0) sufficiently close to (x^*, K^*) there exists a pair (λ_0, μ_0), starting on the two-dimensional manifold that contains (x^*, K^*), satisfying $x(t) \to x^*$, $K(t) \to K^*$ when $t \to \infty$, where $x(t)$ and $K(t)$ are the solutions of (Eq. 25), (Eq. 26) and (Eq. 31).

NUMERICAL EXAMPLES

This section provides an illustration of the model and demonstrates the implications of the optimal steady state policy. Consider a marine area with poor habitats. In order to preserve the resource and associated fishery, it is necessary to design and implement efficient habitat conservation policies. We study the following possibles regulations: interdiction of aggressive fishing techniques; ARs and no effort regulation; optimal steady state policy. These scenarios are compared to each other as well as to the open-access fishery (status quo scenario) in terms of fish stock, carrying capacity and economic rent. The values of economic and ecological parameters are as follows: $r = 0{,}5$, $\tau = 0{,}01$, $\gamma = 0{,}00001$, $K_{\max} = 5000000$, $p = 15$, $c = 100$, $q = 20$, $x_0 = 200000$, $K_0 = 500000$, $E_0 = 170$, $\delta = 0{,}01$.

In order to model the open-access fishery, we use the simple dynamic model of entry and exit developed by Smith [22]. He links the entry and exit to the level of profitability (here $R = \frac{pqx}{K} - c$): $\dot{E} = n\left(\frac{pqx}{K} - c\right)E$, where n is an adjustment parameter and $x(0) = x_0$, $K(0) = K_0$ and $E(0) = E_0$. The model of Smith replicates the main result of Gordon [5] that the economic rent dissipates at equilibrium if no access regulation is applied.

The interdicton of aggressive fishing techniques supposes the use of fishing gears that have a negligeable impact on the habitat. No effort limit is implemented. The equation for carrying capacity is hence as follows: $\dot{K} = \tau K\left(1 - \frac{K}{K_{\max}}\right)$, where $x(0) = x_0$, $K(0) = K_0$ and $E(0) = E_0$.

In this scenario, the carrying capacity of the area increase until $K_{\max}$. At the equilibrium we have the same result of rent dissipation as in the open-access model of Smith. However, under fishing gear regulation fish stock and carrying capacity is better off than in the absence of any restriction (open access). Furthermore, the area can support more fishing vessels.

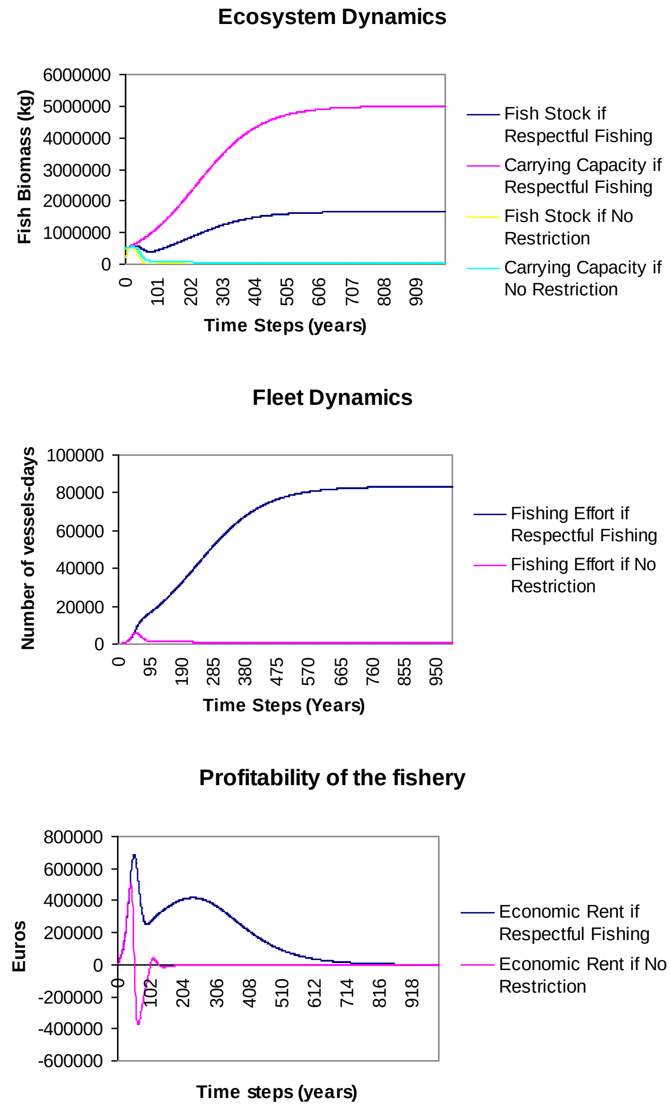

Figure 2. Open access vs. Restriction of fishing techniques

Artificial reefs are immerged in marine areas with highly disturbed habitats. The poor habitats have low carrying capacity. In such a context ARs are expected to enhance the habitat availability and thus area's carrying capacity K. Suppose that ARs policy is implemented without any restriction on the level of effort and their effect on area's carrying capacity is immediate. We also assume that it is possible to estimate which size, quantity and structure of ARs lead to the increase of the carrying capacity such that $K(0) = K^*$ (optimal level). The simulated model is (Eq. 7)-(Eq. 8) where $K(0) = K^*$, $x(0) = x_0$ and $E(0) = E_0$.

Since this policy only affects the initial carrying capacity and does not impose any restriction on the access to the fishery, it is expected that its positive ecological and economic effects cancel out at the equilibrium. In Figure 3 we compare three situations: open access, ARs without management and ARs with effort limit E^*. Note that K^* and E^* are caculated for $\delta = 0{,}01$. We can see that ARs must be managed in order to perpetuate their positive ecological and economic effects.

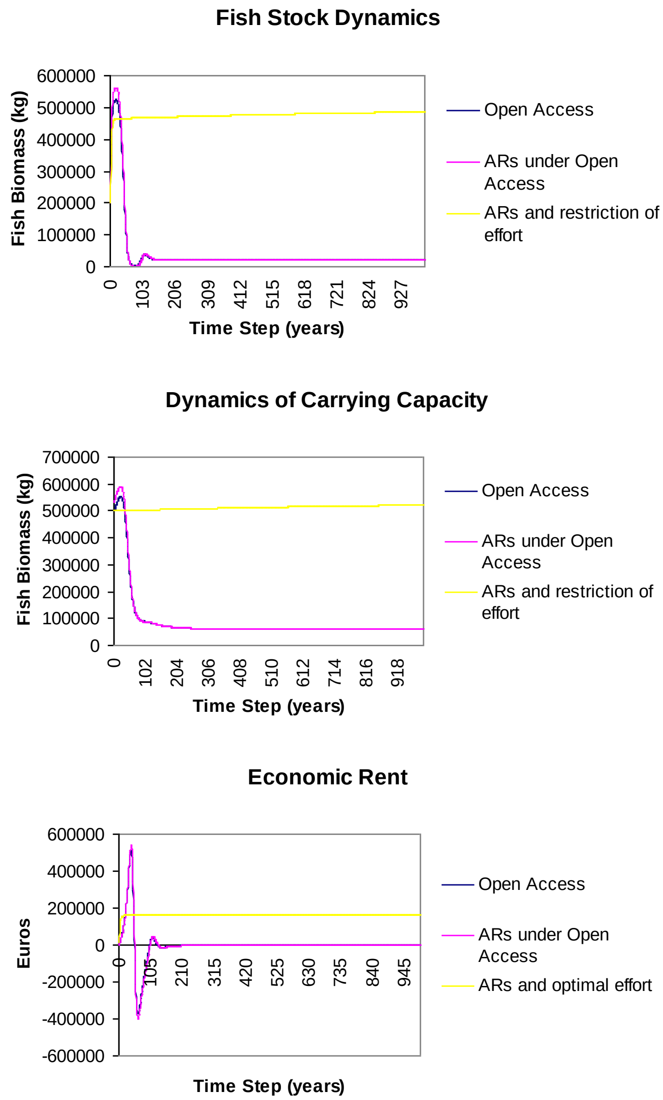

Figure 3. Open access vs. ARs without management vs. ARs with optimal effort

CONCLUSION

In this paper we propose a variation of the G-S model that incorporates the dynamics of carrying capacity. First, it has been demonstrated that habitats matter since, the main outcomes of the G-S model are dramatically modifieed if habitat dynamics is included in the analysis. This result is consistent with the claims of marine biologist and marine managers that habitat deterioration is one of the most important factor in the decline of fisheries in many areas in the world.

Second, assuming that impact of fishing on carrying capacity can be monitored and measured, economically efficient habitat policy can be designed based on this model. Several habitat regulations are analyzed here ranging from restriction of agressive fishing techniques to artificial reefs and combinations of those. On some numerical examples we have shown how the model developed herein allows to study the economic benefits of ecosystem-based management tool such as ARs in a more formalized manner. This particular form of resource management is of interest for coastal ecosystems. The Mediterranean is a good example of such management solutions. Since seventies many ARs were immerged along Mediterranean coasts because artisanal fisheries are in decline in numerous parts of the Mediterranean Sea. Exploited stocks in the Mediterranean Sea suffer high levels of anthropogenic pressure which causes the degradation of the coastal area and overexploitation with implications for target and accessory species as well as for habitats.

According to the optimal steady state policy that we obtain in this paper, a certain level of carrying capacity must be maintained. Since many marine areas are poor in habitats, ARs or other habitat rehabilitation policies (for example MPAs) could be necessary in order to attain this optimal level. Thus this optimal level could represent management objective for artificial reefs policy. At present ARs are, in most cases, implemented when habitats have suffered significant damages (for instance in French Mediterranean). In this perspective the next step would be to study the effects of ARs based on the presented extension of the G-S model. As explained above this management tool is now widely used in coastal areas but its economic interest must still be proven in a rigorous manner. There is the question of artificial reefs management as well. They are economically attractive to fishers due to their ability to concentrate the fish. Too high pressure on reefs areas can mitigate their biological and economic effects. This is the reason why the access to the areas where artificial reefs are immerged must be managed. For this purpose the combination of MPAs and ARs is often employed. Hence in the next study we also want to investigate different management policies for artificial reefs. The examples presented in this paper demonstrates how a formalized model can allow to make a trade-off between simple restriction of effort and the combination of effort limit and ARs as well as the necessity of access regulation to ARs areas.

Further, the results concerning the establishment of MPAs can also be refined based on our model. Obviously, access restriction to marine areas favours recovery of habitats located there. However, existing fishery models do not integrate this fact. If we go even further, we would want to compare MPAs and ARs. Until now it was not possible because of non convenience of existing bioeconomic models. The main difference in these two tools is that they propose different forms of habitat recovery. In the case of ARs, the managment objective is to preserve fish populations by creating habitats. The aim of MPAs is to protect the fish by eliminating fishing pressure in those areas. It is not uncommon for resource managers to combine both tools. All these aspects of fishery management can be addressed based on the model presented in this paper.

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