The Bioeconomic Analysis of Artificial Reefs

Narine Udumyan
GREQAM - Aix-Marseille University, 2 rue de la Charité, 13002 Marseille, France
narine.udumyan@univmed.fr

Abstract

This paper focuses on the economic analysis of artificial reefs, which are known to enhance fish production through the provision of new habitats, and demonstrates analytically their potential for fisheries management. This fisheries management solution is primarily promoted in small-scale fisheries where such projects can have a significant impact on the efficiency of fishermen. The biological research on the topic is abundant whereas economic research is of a much more limited quantity. Even the existing economic literature lacks rigorous analytical framework for the economic analysis of artificial reefs. A simple extension of the existing bioeconomic models with regards to the positive habitat effect of artificial reefs dependent on their size is developed. The economic analysis undertaken in this study yields more pessimistic results than what is found in the purely ecological analysis and in the surveys conducted for real case-studies. According to it, artificial reefs should be accompanied by a limitation of inputs to the fishery or/and an access restriction to ward off the subsequent build-up of fishing pressure in the region. We also solve the problem of a dynamically optimal harvesting with the size of artificial reefs as a policy variable and analyze two funding schemes for the implementation of artificial reef projects in an optimally managed fishery.

Keywords: Artificial reefs, Reserves, Marine habitats, Bioeconomic modelling, Reef management

1. Introduction

The use of controls on input (fishing effort or capacity control) and output (different quota regimes), taxes, subsidies or other economic instruments to manage fisheries is widespread. While in some fisheries, these economic tools succeed in preserving the fishery, many fish stocks continue to decline and the associated fisheries are overcapitalized ([1], [2], [3], [4]). One of the reasons is that ecological attributes of marine ecosystems are neglected when designing fisheries policies. It is the single-stock management paradigm which is usually adopted by resource managers, while biological relationships such as trophic relationships, as well as physical environmental features are omitted. Recent studies addressing the problem of degraded marine habitats show that they are sensitive to some fishing techniques ([5], [6]). In particular, the use of bottom trawling is not permitted in some marine areas due to the danger to the ecosystem (see, for instance, [7]). The existing management paradigms, therefore, appear inadequate.

In this context, a new approach has emerged: Ecosystem-Based Management ([8], [9], [10]), which shifts the fisheries governance focus from managing species independently to the ecosystem-based standpoint. In the last decade we have thus observed a significant body of literature dealing with multiple stocks ([11], [12], [13]), trophic webs ([14], [15], [16]) or habitat issues ([17], [18]). Artificial Reefs (ARs) fit into this concept since they achieve fish management goals principally through targeting the restoration of marine ecosystems. By providing new habitats, they improve the biodiversity of a marine area, on one hand, and are thought to improve the revenues of fishermen thanks to their capacity to aggregate fish and provide better growth conditions, on the other ([19], [20]). Although ARs are used for a long time in small-scale fisheries (the first ARs were immersed in Japan in 17th century), the literature in fisheries economics offers few examples of economic assessment of AR policy ([21], [22]) and very few of these studies yield analytical results (to our knowledge, only the study of Boncoeur et al. [14] has attempted to built a rigorous framework for the analysis of the economic benefits of ARs).

The aim of this paper is to develop a simple bioeconomic model capable of providing a more rigorous analysis of AR policy and provide support to decisionmaking. Using this model we address two important issues. First, we analyze the ecological and economic processes preventing fishing units from enjoying the full benefits of AR policy, and possible responses to them. AR projects frequently do not meet the full expectations of fishery managers. The main reason for this failure is thought to be incorrect management of ARs or even lack of management ([19], [23]). The challenge is to identify the conditions under which the expected ecological and economic benefits of ARs cannot be achieved and what can be done to improve the performance of AR projects. Second, we find a solution to the problem of dynamically optimal management with AR size as a policy variable. We consider two different funding options for the implementation of AR projects. More specifically, either one-shot optimal AR project funded by local government or a sequence of AR projects, the total size of which reaches the optimal level, financed by local fishermen through taxes on fish landings. We examine how efficient these options are in different fishery contexts.

We design and investigate a bioeconomic model of ARs adapted from our earlier model ([24]), which incorporates the negative impact of destructive fishing on a fish population through carrying capacity. In this model, we express the positive habitat effect as a result of the deployment of ARs in increased environmental carrying capacity for the target species for which the deployed ARs provide shelter. We assume that the increase in carrying capacity is an increasing function of the size of ARs, as Armstrong [17] did when modeling the positive habitat effect of an MPA. However, Armstrong [17] uses a standard bioeconomic model, the Gordon-Schaefer model, which does not take into account habitat degradation, a vital issue for fisheries where destructive fishing practices and techniques are observed. In our study, it is all the more important to include these negative habitat effects since it is against this backdrop that AR deployment generally occurs.

Our analysis reveals the importance of two complementary management tools for the success of ARs, effort limitation and reserves. Without the application of at least one of them, the long-term benefits of ARs are strongly jeopardized both ecologically and economically. In addition, the importance of gear regulations becomes transparent throughout this study.

To achieve the dynamically optimal levels, our analysis suggests the creation of a temporary reserve, which will allow ARs to be colonized by marine organisms (during this period carrying capacity will gradually increase until the optimal level). In the case of exogenous and fixed effort, we find that under lowly or highly intensive fishing ARs are of little benefit. In the case where the fishing effort is regulated together with AR size, AR projects appear useful in costly fisheries (the optimal AR size is the maximal possible size). Finally, we show that when facing a choice of AR funding methods, one of the factors that should be considered is the time required for the bioeconomic system to converge to the optimal levels. If it is possible to fund and realize the construction and installation of the optimal amount of ARs in one large project in initial period, then faster convergence can be assured. However, if the optimal AR size is too large, such investment is too demanding for the local government's budget than the application of a number of small AR projects through the implementation of taxes.

The paper is organized as follows. The next section detail the functioning and the purposes of ARs and reviews the challenges. Section 3 presents a general bioeconomic model of ARs and its special case. Section 4 examines the equilibrium properties of the model and analyzes standard management scenarios involving effort and gear control. In section 5, the problem of dynamically optimal management is addressed with AR size as a policy variable in the context of two different funding schemes. Section 6 discusses the main results and concludes.

2. The role of ARs in the fisheries management and the existing challenges

According to fisheries scientists, ARs assume the role of natural habitats. For certain species (principally, rock fish) ARs provide shelter. They protect juveniles from predators. For some species, ARs are also spawning areas (for example, cephalopods). Two general types of ARs are distinguished: ARs designed with the goal of enhancing the resource and generating higher financial returns ([25]) and ARs built primarily with the purpose of preventing the use of certain destructive fishing techniques prohibited in the fishery ([26]). The first kind of reef units is seen as a tool for sustaining coastal fisheries through the mitigation of the effects of stock depletion. The second type of ARs is more an enforcement device designed to make the resources inaccessible to certain types of gear. In Europe, they are commonly used to exclude illegal trawling from sensitive habitats ([27]).

In this paper, the focus is on the first type of ARs, which is expected to improve the profitability of the local fishery thanks to the surplus of fish biomass. However, it is important to mention that among fisheries scientists there is a scientific debate on whether ARs act only to attract and aggregate fish or also to increase fish biomass ([28], [29], [30], [31]). Some studies have pointed to the capacity of ARs to act as production enhancers ([32], [33]), others have not ([34], [35]), which is probably related to the improper design of reef units as well as the absence of a management strategy dealing with the build-up of fishing pressure that ARs may engender ([19]).

Baine [36] conducts a thorough literature review on the issues raised due to the implementation of AR projects (essentially carried out in North America). With regards to the existing case-studies, he concludes that ARs have the potential to meet the full expectations of their promoters but on condition that the prior planning and ongoing management is afforded to ARs. [23] also supports this point of view and argues that the implementation of AR projects imposes additional demands on the regime of management controls (see also [37], [38], [39]). In this section, we will give more details on the existing challenges regarding the deployment of ARs that will be taken up in the present study.

2.1. Do the expected and observed benefits of AR projects match?

ARs are deployed for a variety of purposes. The most common goals are: enhancement of fisheries yield and production ([40], [41]), mitigation of local habitat damage or loss ([36], [42]), prevention of trawling ([26], [43]), recreational fishery and diving ([44], [45]) and research on fish populations and epifauna ([46]).

Thus, ARs are expected to yield a range of economic benefits ([23]). There are direct use benefits such as increased catches both for commercial and recreational fishermen. Thanks to the diversified fauna and flora, ARs also provide beautiful scenery, which favors the development of diving tourism. In that case, the direct use benefits are expressed in an increased economic activity through the injection of new money into local economy. Indirect use benefits include increased fish production (due to the protection of juveniles or the diversion of effort from overexploited fisheries), coastal and shoreline protection, and improved water quality through the attraction of nutrient-removing organisms. Finally, non-use benefits (such as existence values) can also be generated: non-users of ARs may perceive their existence as beneficial to the marine environment of the region.

Surveys conducted in different parts of the world confirm the positive implications of AR projects for both marine ecosystem and fishermen. In particular, according to them, ARs succeed in raising catch rates as well as economic returns ([28], [47], [25]). However, these surveys usually reflect short- or, at most, medium-term outcomes. The time elapsed after the deployment of ARs is not enough to certify that these benefits will persist in the long term. Based on our model, we compare the predicted long-term benefits to the observed short-term benefits and explain why they do not always match.

2.2. Difference from other habitat recovery measures and the resulting non-coherence of the existing modeling solutions

Aside from ARs, other habitat-conservation management tools are widely applied. Reserves allow the recovery of habitats located within their boundaries through complete elimination of effort in the area ([48], [49]). Another example is gear regulations in the shape of a ban on fishing practices and methods that are destructive for the marine environment. The main difference between ARs and these tools is that they achieve habitat conservation by preventing habitat degradation induced by destructive fishing whereas ARs provide new habitats but habitat degradation can still persist if reef units are not designed specifically for this purpose. The few studies on the bioeconomic modeling of AR effects do not take into consideration this important feature ([22], [50]). This is the reason why the effects of reserves and those of ARs are often confused and are modelled similarly. We show that the model developed in this study leaning on our earlier model provides a framework in which the difference between these tools can be taken account of.

2.3. Importance of AR management

Together with the positive observations on the performance of AR systems, the existing surveys also hold a warning. The spatial behavior of fishermen modifies when ARs are immersed. The opportunities opened up by ARs draw fishermen to the AR area as soon as they recognize their benefits, which can lead to the overall increase of fishing pressure in the region. The risk of overexploitation is all the more significant when ARs function as a concentration device that attracts fish from the surrounding areas, rather than as an enhancer. Thus, fished ARs have the potential to lead to a sever overfishing ([28], [51]). This is the reason why it is recommended to accompany AR projects with complementary measures aiming at limiting fishing pressure in the region. It is usually suggested to restrict the access to AR areas or adopt effort control. The restrictions can be partial in the shape of a ban on particular fishing activities or particular types of gear or absolute such as a reserve. The latter tool creates a safe area for fish populations and allows the colonization of ARs to occur in more favorable conditions. In that case, the fishing units benefit from the exportation of the biomass from this area to fishing grounds. The area closure can also be temporary and its only purpose is to allow the initial colonization of ARs by fish communities as well as other marine organisms. After this period is respected, the ban on fishing activities is lifted. We identify the conditions under which these additional management controls are necessary for the success of AR projects.

2.4. How AR projects are funded?

To produce considerable effects, large-scale AR projects should be implemented. They require large investments including the costs of labor and materials used both in the preparation phase of the project (definition of objectives, the analysis of the marine environment to ensure a proper design of ARs) and the main phase (design, construction and immersion). Financial costs associated with the deployment of ARs are covered in various ways. They can be funded by local governments in the form of grants, by using decommissioned vessels as reef units or involve volunteer efforts to name a few of them ([45]). If on-going management costs are involved (for instance, to monitor and punish any illegal activity in the AR area), then AR users can be asked to pay a fee to bear the expenses.

Thus, the major part of expenses is borne by local authorities, which makes the deployment of AR projects subject to their budgets or the existing financial aides. Large-scale project have little chance to be developed and realized. We hence analyze a funding scheme that allows the construction and the installation of ARs at the expense of fishing units operating in the AR area by imposing a landing tax referred to as the catch royalties by [52].

3. The Bioeconomic Model of ARs

The model developed herein is based on our earlier model ([24]), which integrates the observation, supported by numerous biological studies and surveys, that environmental carrying capacity is strongly related to the state of habitats (see, for instance, [53]). This link between habitats and carrying capacity is important when the performance of AR projects is evaluated. Anthropogenic interventions such as fishing and the implementation of ARs have both an important impact on habitats and, therefore, on the carrying capacity of the marine environment. Specifically, the deterioration of habitats caused by destructive harvesting can result in decline of carrying capacity for fish populations (see [6]) whereas the rehabilitation of habitats through ARs leads to increased carrying capacity. Our model incorporates both effects and allows for interactions between them.

We first present Udumyan et al.'s [24] benchmark model (both general model and a special case) and then explain how it is modified to incorporate the effects of ARs.

3.1. Benchmark model

Fish stock dynamics. Udumyan et al.'s Udumyan et al. [24] benchmark model is based on the Gordon-Schaefer model ([54], [55]), which describes the dynamics of the fish stock x as follows:

$$\dot{x} = F(x, K) - H(x, E), \tag{1}$$

where $F(x)$ denotes the natural growth rate of fish and the function $H(t)$ represents harvests.

Standard assumptions are adopted on the above functions:

$F(x, K) = rx(1 - x/K)$ with r the intrinsic fish growth rate, $r > 0$, and K the environmental carrying capacity, $K > 0$;

$H(x, E) = qEx$ with q the catchability coefficient, $q > 0$, and E the fishing effort, $0 \leq E \leq E_{max}$. The parameter q relates to the effectiveness of the employed fishing technology. The effort E is "a composite index of all inputs employed for the purpose of realizing this catch" (FAO).

Carrying capacity dynamics. While in standard models carrying capacity is a fixed parameter, Udumyan et al. [24] represent carrying capacity as a state variable endowed with its own dynamics to account for the negative habitat effect of fishing:

$$\dot{K} = D(K) - G(K, E), \tag{2}$$

where $D(K)$ is the growth rate of carrying capacity due to habitat recovery and $G(K, E)$ stands for the loss rate of carrying capacity caused by fishing.

Since habitat is not simply a physical structure but encompasses the fauna and flora that colonizes it, Udumyan et al. specify the function $D(K)$ as a logistic function, which gives a good description of the growth of living populations

$$D(K) = K(1 - K/K_{max}) \tag{3}$$

with τ the growth rate of carrying capacity, $\tau > 0$, and K_{max} the maximal possible carrying capacity, $K_{max} > 0$.

The idea behind this growth function is that the target fish species is ecologically dependent on other (plant and animal) marine species that share the same habitat. With their growth, more food is available for the target species, and thus better conditions are provided for its growth, which has a positive repercussion on the carrying capacity for this species.

The function $G(K, E)$ follows the assumption of proportionality

$$G(K, E) = \gamma EK \tag{4}$$

with γ loss rate of carrying capacity, $\gamma > 0$.

This function embodies the negative habitat effect of fishing when destructive fishing gear ($\gamma > 0$) is employed. The higher the parameter γ, the more destructive the fishing gear employed. The extreme case is $\gamma = 0$, which reflects the use of a habitat-friendly gear.

According to (1), carrying capacity below its upper limit K_{max} grows as long as $D(K) > G(K, E)$, shrinks when $D(K) < G(K, E)$ and remains unchanged if $D(K) = G(K, E)$. It is this last situation that is assumed in the Gordon-Schaefer model.

Special case. When a strong assumption of instantaneous impact of fishing on habitats is adopted, the special case of the Udumyan et al.'s model is obtained:

$$\dot{x} = rx(1 - \frac{x}{K(E)}) - qEx, \tag{5}$$

$$K(E) = K_{max}(1 - \theta E), \tag{6}$$

where θ has the same interpretation as the parameter γ, i.e. loss rate of carrying capacity. Following (6), for a given effort, carrying capacity is constant. From this follows another special case, $\theta = 0$, which corresponds to the standard Gordon-Schaefer model.

3.2. Modeling the effects of ARs

As mentioned previously, we are interested in the reef units which are only aimed at the rehabilitation of fish populations and habitats and not thought of as an enforcement device. Suppose that such units are immersed in the area under consideration and α is their overall size measured, for instance, in m3, $0 \leq \alpha \leq \alpha_{max}$.

Main assumption. Without taking part in the "attraction versus production" debate ([19]), we simply refer to an undeniable fact that AR projects result in the creation of new habitats for the fish ([28], [56], [30]). Since a positive relationship is found between habitats and carrying capacity, our main assumption is that the deployment of ARs leads to the increase of the maximal possible level of carrying capacity in the area under survey[1]. In this respect, carrying capacity can grow to

[1] Another potential effect of ARs, not taken into account in this study, is increased intrinsic fish growth rate r.

a higher level than in the absence of ARs. It is important to note that only the habitat effect of ARs is taken into account in this study and their concentration effect, consisting in a facile extraction of fish, is neglected[2].

General model. According to the claims of marine biologists, some period of time is required for ARs to become habitable through the process of fauna and flora colonization, that is, to offer shelter, protection and food to the target fish species[3]. Representing carrying capacity as a dynamic variable allows to take account of this observation. Thanks to this representation, ARs can be modeled as physical structures that slowly become habitable through gradually increasing carrying capacity for the target fish species, which is what real fisheries usually experience. The general model of ARs is thus described by the following system:

$$\dot{x} = rx(1 - \frac{x}{K}) - qEx, \tag{7}$$

$$\dot{K} = \tau K \left(1 - \frac{K}{K_{max} + L(\alpha)}\right) - \gamma EK, \tag{8}$$

$$x(0) = x_0, K(0) = K_0.$$

where α stands for the size of ARs immersed in the marine area and $L(\alpha)$ for the amount of carrying capacity by which the maximal carrying capacity increases.

The function $L(\alpha)$ is increasing and captures the positive habitat effect of ARs. We assume that $L(\alpha) = \tilde{K}\alpha$ where $\tilde{K}$ is the increase in carrying capacity per reef unit.

Both positive and negative habitat effects are time-dependent. They can only be witnessed in the future periods of time.

[2]The concentration effect of ARs is usually taken into account though increased catchability coefficient q. This effect raises a number of concerns. In particular, Milon [37] puts forward the "paradox of artificial habitat development" that increased effectiveness of fishing units due to the aggregation of fish in ARs may threaten the economic performance of the fishery if no additional regulations are in place.

[3]For instance, a Portuguese study shows that the productivity of ARs rose throughout the observed period of 15 years. This points to complex processes occurring between the hard substrate and the marine environment, implying that it takes time for ARs to have their full effect on carrying capacity (see, for instance, [23]).

Special case. Since the general model can lead to non tractable results, we simplify the model when the general model fails to yield analytical results. Not only we assume an instantaneous impact of fishing on habitats but also an instantaneous colonization of ARs by marine organisms meaning that both positive and negative habitat effects are no longer dependent on time and the increase as well as the decrease in carrying capacity are instantaneous. Thus, our bioeconomic system reduces to

$$\dot{x} = rx\left(1 - \frac{x}{(K_{max} + \tilde{K}\alpha)(1 - \theta E)}\right) - qEx, \tag{9}$$
$$x(0) = x_0.$$

3.3. Economic assumptions, evaluated fisheries management scenarios and observed indicators

The implementation of AR policy and the measures of its benefits. We assume that ARs can be deployed only once in all examined scenarios except for the optimal taxation problem (see Section 5.3) where AR projects are implemented each period of time as long as the taxes collected in this period and used to cover them are not nil. When the equilibrium behavior of our model is investigated, we understand by the long-term ecological benefits of ARs any increase in the steady-state fish stock. The long-term economic benefits are measured in terms of sustainable rent.

Investments in AR projects. The function $C(\alpha)$ denotes a discrete investment in an AR project, which is incurred in period 0 and related to the labor and materials spent for the design, construction and immersion of ARs. A unique payment is assumed for each AR project, thus neglecting any on-going maintenance and management costs (in some cases, they can be significant [45]).

Economic rent. Each period of time, fishing units spend a constant cost c per unit of effort to harvest fish using a fishing technology determined by the catchability coefficient q, measure of efficiency of fish extraction, and the destruction parameter γ[4] (or θ), measure of aggressiveness in regards to habitats. They sell it on the market at a constant price p. The cost c includes the costs of operating vessels (fuel,

[4] We assume that artificial habitats have the same sensitivity to fishing as natural habitats, i.e. the parameter γ is identical for both types of habitats.

supplies etc.) plus opportunity wages of captain and crew ([52]). The price p and the cost c are assumed to be exogenous since we focus on small-scale fisheries where AR projects are usually promoted and put in place. The overall quantity offered on the market by these fisheries is not large enough to affect the market price and thus agents are price takers. Thus, the total revenues derived from the fishery after the immersion of ARs is $R(x, E) = pqEx - cE$.

Combined management scenarios. When an AR project is implemented, it can be combined with complementary fisheries management tools to avoid potential negative "side" effects mentioned in the previous section. Specifically, we analyze the following three management controls: effort limitation, gear regulations and access restrictions.

In the first group of scenarios, the AR size is assumed exogenous and the fishery objective is to maximize the sustainable rent of fishery meaning that the present and future benefits are equally weighted. First, traditional effort limitations based on the widely used concepts of the MSY and the MEY are examined and compared to other level of efforts in terms of AR performance. Second, gear regulations are investigated via the habitat destruction parameter γ and three options are compared: any type of fishing gear is allowed, $\gamma > 0$, and ARs are deployed, $\alpha > 0$; the destructive types of gear are prohibited, $\gamma = 0$, but ARs are not deployed, $\alpha = 0$; the combination of both, i.e. $\alpha > 0$ and $\gamma = 0$. The scenarios in this group are also compared for different AR size levels.

In the second group of scenarios, the AR size is represented as a control variable and the objective is to maximize the discounted rents of fishery (the present benefits have more weight than the future benefits). First, the dependence of the optimal AR size on the effort level is inspected. Second, the effort is considered as a policy variable together with the AR size; the role of a temporary reserve is investigated; two AR funding options are compared: unique funding by a local government or a sequence of AR projects financed through taxes on fish landings.

Indicators. When assessing the first group of scenarios, we focus on economic issues such as resource rent and harvest as well as environmental issues such as stock level and protection against extinction and observe them via three indicators: steady-state fish stock, sustainable yield and sustainable rent.

4. Equilibrium analysis

In this section, we examine the equilibrium behavior of the presented model. Expression for biological equilibria is found and analyzed. The long-term implications of AR policy are discussed and its combination with other fisheries management tools is assessed for a fixed size α of ARs. We start by examining the worst possible scenario where no management is afforded to ARs after their deployment, that is, an unregulated open-access fishery. Then two standard effort limitations Maximum Sustainable Yield (MSY) and the Maximum Economic Yield (MEY) that satisfy the common objectives for fisheries management are studied (see, for instance, [57]). Finally, the impact of the most restrictive gear regulation - ban on the use of any destructive fishing gear - on the performance of ARs is analyzed.

4.1. Biological equilibria

The biological equilibria are derived from the equations $\dot{x} = \dot{K} = 0$. The model given by (7) and (8) possesses one positive steady state:

$$\overline{x} = (K_{max} + \alpha\tilde{K})(1 - \gamma E/\tau)(1 - qE/r); \tag{10}$$

$$\overline{K} = (K_{max} + \alpha\tilde{K})(1 - \gamma E/\tau). \tag{11}$$

This steady state is locally asymptotically stable[5].

As expected, the positive habitat effect due to the deployment of ARs results in higher steady-state fish stock (according to the first multiplier in equation (10)). The second multiplier in expression (10) accounts for destructive harvesting resulting in the deterioration of both natural and artificial habitats whereas the third multiplier refers to the fishing mortality caused by fishing. With respect to the second multiplier, when destructive harvesting takes place ($\gamma > 0$), any additional unit of effort reduces the ecological benefits of ARs. It then follows that when fishing

[5] To show this, the system (7)-(8) is linearized at $\overline{x}, \overline{K}$. Then, the Jacobian of the system is found $V(\overline{x}, \overline{K}) = \begin{pmatrix} qE - r & r\left(1 - \frac{qE}{r}\right)^2 \\ 0 & \gamma E - \tau \end{pmatrix}$. Due to the positivity condition of $\overline{x}$ and $\overline{K}$, $qE - r < 0$ and $\gamma E - \tau < 0$ and, thus, the eigen values of this matrix are negative. Consequently, $(\overline{x}, \overline{K})$ is locally asymptotically stable.

is not allowed in the AR area, ARs fare the best from the biological point of view. When the area is open to fishing and the fishing effort cannot be regulated, the prohibition of destructive types of gear ($\gamma = 0$) is the second-best solution for the improvement of ecological benefits of ARs.

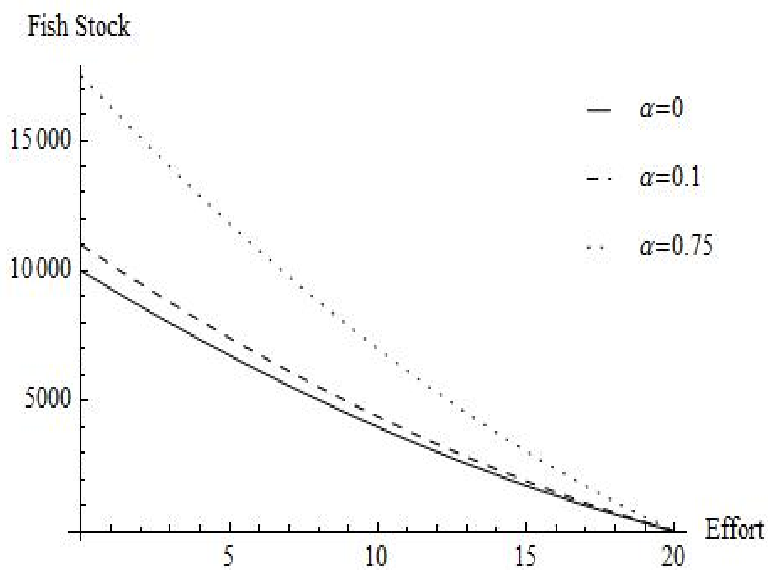

Figure 1: The steady-state fish stock as a function of effort is displayed for different values of α. The parameter values are $r = 0.1, q = 0.005, \tau = 0.05, \gamma = 0.001, K_{max} = 100000, \tilde{K} = 10000$.

Figure 1 compares steady-state fish stocks for different sizes of AR projects (dashed and dotted curves) with the fish stock produced in their absence (normal curve). The gap between the curves decreases as effort increases and the fish stocks corresponding to a positive α (dashed and dotted curves) approach that of the status quo scenario $\alpha = 0$ (normal curve). Thus, in a heavily fished fishery, there is little ecological benefit from the deployment of ARs and there are two reasons for this. First, the quantity of fish extracted increases with increasing effort and ARs cannot remedy this since they do not correct the underlying economic incentives. Second, the impact of destructive harvesting on habitats amplifies as effort increases and, at high levels of effort, this strongly impairs the positive habitat effect of ARs. At lower efforts, the gap between the curves broadens accentuating the positive consequences of an AR project. The ecological benefits of ARs increase as α increases.

This preliminary analysis illustrates that the performance of AR projects strongly depends on the effort exerted in the AR area. It supports previous theoretical studies (for review, see [23]) and empirical observations, asserting that the fishing pressure in AR areas should be controlled for fishing units to benefit from the surplus of the fish attracted/produced by ARs. In the next subsections, more detailed analysis will be carried out to develop this idea.

4.2. Unregulated open-access fishery: is there any benefit from ARs?

We are interested in the open-access scenario since it is frequently observed that for social, cultural, political or other reasons, the intervention of local government is not welcomed by small fishing communities who usually show interest in AR projects ([58]). When an AR policy is implemented in such a context, their ecological benefits are limited, as our previous analysis show, and the only expectation from it is to facilitate resource exploitation as a concentration device and enhance fishery harvest through the mitigation of habitat damage or loss (see, for instance, [59]). These goals aside, fishery managers also expect to observe increase in fishermen's profits. A number of surveys were carried out that confirm these economic benefits ([28], [33], [47], [25]). The efficiency of the fishermen operating in the AR area improves, which is reflected in higher monetary returns at the ARs and increased catches per unit of effort. However, these are short-term benefits. The question is whether they are sustained in the long term when AR policy is not complemented by any access or effort regulation.

In an unregulated open-access fishery effort achieves a bioeconomic (or bionomic, as Clark refers to it) equilibrium at the level E_{OA} where fishery revenues match cost, i.e. $pH(x, E) = cE$:

$$E_{OA} = \frac{1}{2}\left(\frac{r}{q} + \frac{1}{\gamma}\right) - \sqrt{\left(\frac{1}{2}\left(\frac{r}{q} + \frac{1}{\gamma}\right)\right)^2 - \frac{r}{q\gamma}\left(1 - \frac{c}{pq(K_{max} + \alpha\tilde{K}}))\right)}. \qquad (12)$$

It is evident that, in an unregulated open-access fishery, AR projects do not meet the goal of improving the rents of the fishery on the long-term basis. The short-term increase in profits engendered by the deployment of ARs triggers the process of effort adjustment (entry of new fishing units or/and the expansion of the fishing activities of the existing fishing units) until the rent of the fishery dissipates. The long-term ecological benefits of ARs also decimate under open access. The fish stock converges to the same level as in the absence of ARs, $x_{OA} = \frac{c}{pq}$. Even though, in the short term, the creation of new habitats will attract fish populations and favor their reproduction, thus improving the short-term profits of fishermen, as reported by the ecological surveys discussed earlier.

This result is intuitive since the problem of fishery overcapitalization is not supposed to be solved by the immersion of ARs and still persists. The lack of control over fishing activities makes AR policy ineffective from both ecological and economic points of view. However, even in this worst-case scenario in terms of regulation, a positive implication can still be ensued from applying this policy. Owing to the attraction/production effect of ARs, higher quantity of fish can be extracted in this fishery, i.e. $qE_{OA}x > q\widehat{E}_{OA}x$, where $\widehat{E}_{OA}$ is the bionomic equilibrium effort level calculated for a bioeconomic system without ARs, $\widehat{E}_{OA} = \frac{1}{2}\left(\frac{r}{q} + \frac{1}{\gamma}\right) - \sqrt{\left(\frac{1}{2}\left(\frac{r}{q} + \frac{1}{\gamma}\right)\right)^2 - \frac{r}{q\gamma}\left(1 - \frac{c}{pq(K_{max}}\right)}$. It is important to note that this increase in catches is not the consequence of an increased standing fish stock but of the expansion of fishing activities, i.e. higher open-access effort is sustained by the ecosystem due to the extraction of additional fish recruits produced/attracted by ARs. Hence, in the long term, catches per unit of effort (CPUE) remain the same as in the absence of ARs contrary to what is reported by surveys conveying short-term benefits. Even so, we cannot tell definitely whether the efficiency of fishermen does not improve at all since reef units can affect the catchability coefficient q due to their concentration effect but it is unlikely that this effect will have a significant impact on the long-term performance of fishermen.

Higher catches is the result of the offset of ARs against habitat loss. For a sufficiently large AR project, the negative impact of habitat degradation on catches is entirely alleviated. As depicted by Figure 2, when $\widehat{\alpha} = \frac{a}{\bar{K}(1-a)}$ with $a = \frac{r\gamma}{q}\left(1 - \frac{c}{pqK_{max}}\right)$, the catches sustained by ARs equal the catches resulting from habitat-friendly fishing without ARs. At this size, the positive habitat effect produced by ARs compensates the negative habitat effect engendered by the use of destructive types of fishing gear. With respect to this, we can say that ARs fulfill the role of habitat loss mitigation in terms of foregone catches in the long term as well.

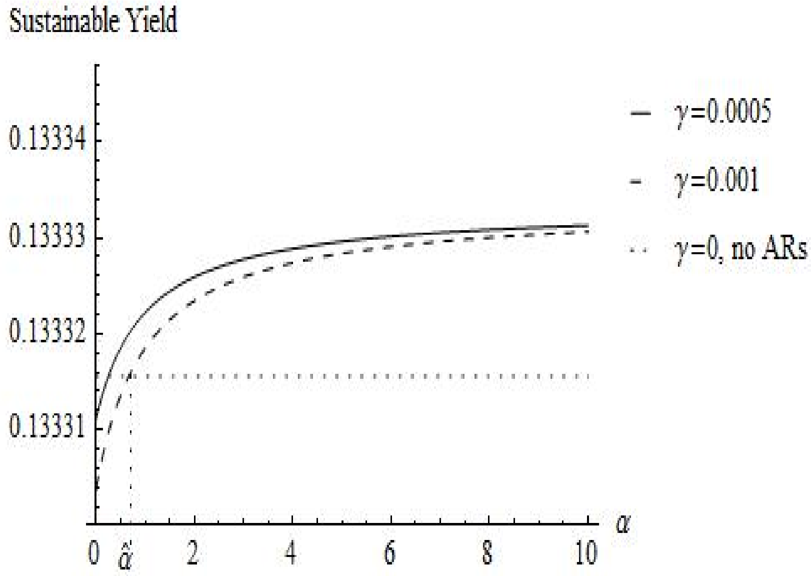

Figure 2: The sustainable yield as a function of α in an open-access setting. The dashed and the normal curves correspond to $\alpha > 0$ and the use of destructive gear, while the dotted line to the absence of ARs and the use of habitat-friendly gear. The AR size $\widehat{\alpha}$ is the threshold at which the negative habitat effect caused by destructive fishing is entirely offset by the positive habitat effect of ARs.The parameter values are $r = 0.1, q = 0.005, \tau = 0.05, \gamma = 0.001, K_{max} = 100000, \tilde{K} = 10000$.

But this positive implication is not enough to regard ARs as a tool dealing with habitat degradation. According to our model, the use of destructive types of gear can decrease the critical level of effort $E_{crit} = min\left\{\frac{1}{\gamma}, \frac{r}{q}\right\}$, at which fish goes extinct. When $\frac{1}{\gamma} < \frac{r}{q}$, this level falls to $E_{crit} = \frac{1}{\gamma}$ and cannot be extended by simply providing new habitats to fish. When reef units are not designed with the purpose of preventing destructive fishing, the associated marine ecosystem and local fish populations still remain vulnerable to destructive gear. In real ecosystems, even more complex adverse processes occur that cannot be taken into account by our model. The food chains get disturbed, the trophic structure changes leading to ecological imbalance and some of these processes are irreversible.

The French Mediterranean small-scale fisheries are an example of weak governmental regulations of fishing activities. In general, when ARs are just immersed, a temporary ban on fishing in the AR area is put in place to allow the fish communities to colonize ARs. However, after several years the ban on fishing is lifted and the fishing activities in the AR area is no longer subject to a strict control. Our analysis shows that in such a context attempts to improve the long-term profitability of the fishery are destined to fail. The opportunities opened up by ARs draw additional fishing units to the AR area. And even if increased catches can be achieved, the reason is that the marine environment is able to sustain higher effort and not higher fish stock. The build-up of fishing effort can put in danger the target fish species of the entire region when increased catches are solely the result of the attraction of fish from other areas.

4.3. Effort restrictions

The complete dissipation of economic rent in an unregulated open-access fishery constitutes a loss to society. To preserve at least a part of the rent, Gordon [54] recommends to limit effort to some level below bionomic equilibrium. For this reason, two traditional references for sustainable resource exploitation such as the MSY and the MEY were elaborated ([57]). The idea behind the MSY is to determine the maximal quantity of fish that can be extracted without altering the fish stock. At the MSY and lower levels of effort, the "biological" overfishing resulting from the impossibility to maintain the maximal possible growth of fish allowed by the marine environment can be avoided. The MEY refers to the yield level at which sustainably harvested fish stock produces the greatest economic rent, which helps to avoid the "economic" overfishing. These references are determined on the basis of the Gordon-Schaefer model. We apply these concepts in the framework of our model to take account of the negative habitat effects caused by fishing as well as the positive effects yielded by ARs.

The effort level leading to the MSY in our framework is

$$E_{MSY} = \frac{1}{3}\left(\frac{r}{q} + \frac{\tau}{\gamma}\right) - \sqrt{\frac{1}{9}\left(\frac{r}{q} + \frac{1}{\gamma}\right)^2 - \frac{r\tau}{3q\gamma}}, \tag{13}$$

$$x_{MSY} = (K_{max} + \alpha\tilde{K})\left(1 - \frac{1}{3}k_1 - \frac{1}{3}k_2 + \frac{1}{27}\left(\frac{r\gamma}{\tau q} + \frac{\tau q}{r\gamma} + 2\right)\left(\frac{r\gamma}{3\tau q} + \frac{\tau q}{3r\gamma} + \frac{50}{3}\right)\right) \tag{14}$$

where $k_1 = \sqrt{\frac{1}{9}\left(1 + \frac{\tau q}{r\gamma}\right)^2 - \frac{\tau\gamma}{3rq}}$, $k_2 = \sqrt{\frac{1}{9}\left(1 + \frac{r\gamma}{\tau q}\right)^2 - \frac{rq}{3\tau\gamma}}$

and to the MEY

$$E_{MEY} = \frac{1}{3}\left(\frac{r}{q}+\frac{\tau}{\gamma}\right) - \sqrt{\frac{1}{9}\left(\frac{r}{q}+\frac{1}{\gamma}\right)^2 - \frac{r\tau}{3q\gamma}\left(1-\frac{c}{pq(K_{max}+\alpha\tilde{K})}\right)}, \qquad (15)$$

$$x_{MEY} = (K_{max}+\alpha\tilde{K})\left(1+\frac{1}{9}l_1-\frac{1}{3}l_2-\frac{1}{3}l_3+\frac{1}{27}\left(\frac{r\gamma}{\tau q}+\frac{\tau q}{r\gamma}+2\right)\left(\frac{r\gamma}{3\tau q}+\frac{\tau q}{3r\gamma}+\frac{56}{3}-2l_1\right)\right) \qquad (16)$$

where $l_1 = 1 - \frac{c}{pq(K_{max}+\alpha\tilde{K})}$, $l_2 = \sqrt{\frac{1}{9}\left(1+\frac{\tau q}{r\gamma}\right)^2 - \frac{\tau\gamma}{3rq}\left(1-\frac{c}{pq(K_{max}+\alpha\tilde{K})}\right)}$, $l_3 = \sqrt{\frac{1}{9}\left(1+\frac{r\gamma}{\tau q}\right)^2 - \frac{rq}{3\tau\gamma}\left(1-\frac{c}{pq(K_{max}+\alpha\tilde{K})}\right)}$.

As can be seen from expressions (13) and (15), the negative habitat effect of destructive fishing undermines the capacity of the ecosystem to sustain fishing activities. The higher the habitat destruction parameter γ, the lower the efforts E_{MSY} and E_{MEY} as well as the fish stocks x_{MSY} and x_{MEY}. The positive habitat effect of ARs allows the ecosystem to underpin higher E_{MEY} but E_{MSY} is not affected by it (see Figure 3). As for the fish stocks x_{MSY} and x_{MEY}, they are both positively related to α. The reason for this positive relation between E_{MEY} and α, i.e. $\frac{\partial E_{MEY}}{\partial \alpha} > 0$, lies in the improvement of fishery efficiency imputable to better conditions for fish growth offered by ARs: the unit cost of effort remains unchanged but greater revenues per unit of effort are earned since the population of fish is larger and, therefore, more fish can be captured.

To compare the performance of ARs for different levels of effort, let us observe the behavior of three indicators - fish stock, sustainable yield and sustainable rent - depending on effort level.

Sustainable yield and sustainable rent are increasing functions of the size α of ARs: the larger the scale of an AR project, the greater the produced surplus in the sustainable yield and the sustainable rent. Obviously, the value of α maximizing sustainable yield is the upper bound α_{max}. Because the present and future revenues are equally discounted and no managements and maintenance costs are incurred, the amount invested in an AR project does not affect the size α of ARs at which the sustainable rent is maximized, it hence also equals α_{max}. Figure 5 illustrates sustainable yield as a function of effort for different values of α while Figure 6

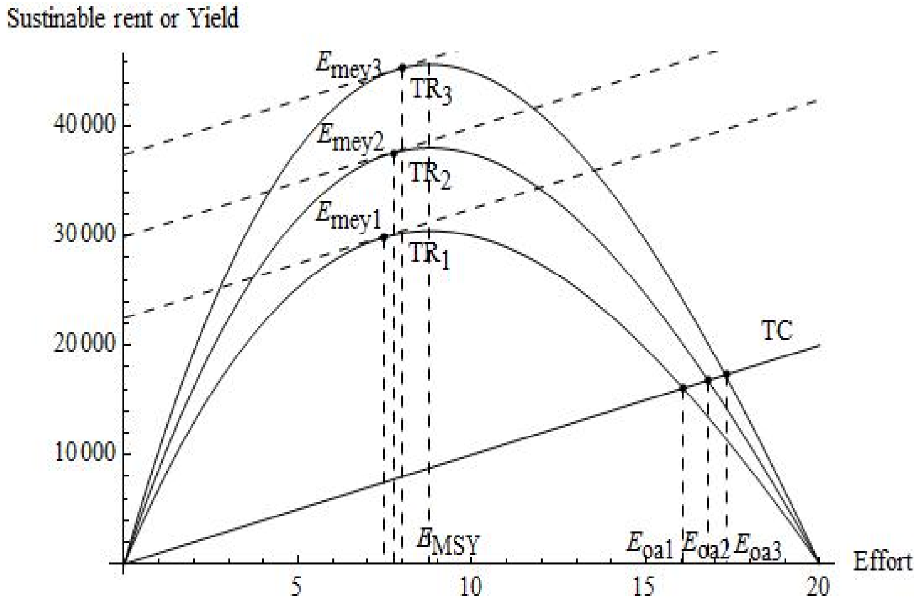

Figure 3: This graph shows how E_{MSY} and E_{MEY} are obtained and their relation to α. TR1 describes the sustainable rent corresponding to $\alpha = 0$, TR2 to $\alpha = 2.5$, TR3 to $\alpha = 5$. TC represents the cost of fishing. The parameter values are chosen as follows: $p = 15$, $c = 1000$, $r = 0.1$, $q = 0.005$, $\tilde{K} = 10000$, $\tau = 0.05$, $\gamma = 0.001$.

portrays the corresponding sustainable rent. In each figure, the gaps between the curves considerably decrease as they approach to very low or very high efforts. This shape of the curves suggests that ARs become less effective and almost useless for a lightly or a heavily exploited fisheries since, in that case, fishing units realize low catches. The benefits derived from ARs in a lightly exploited fishery are almost solely ecological - fish stock increases (see Figure 4). Since, in that case, the fishery is underexploited, ARs yield little economic benefit. The worst situation arises in a heavily exploited fishery where, together with acute fishing mortality, habitats whether they are natural or artificial are severely degraded and both ecological and economic benefits of ARs are jeopardized (see Figures 4 and 6). In terms of sustainable yield, AR policy is the most effective at the effort level E_{MSY} while, in terms of sustainable rent, at E_{MEY}.

Thus, as expected, the efficiency of AR policy can be greatly improved from both ecological and economic points of view, if it is possible to regulate fishing pressure in the fishery.

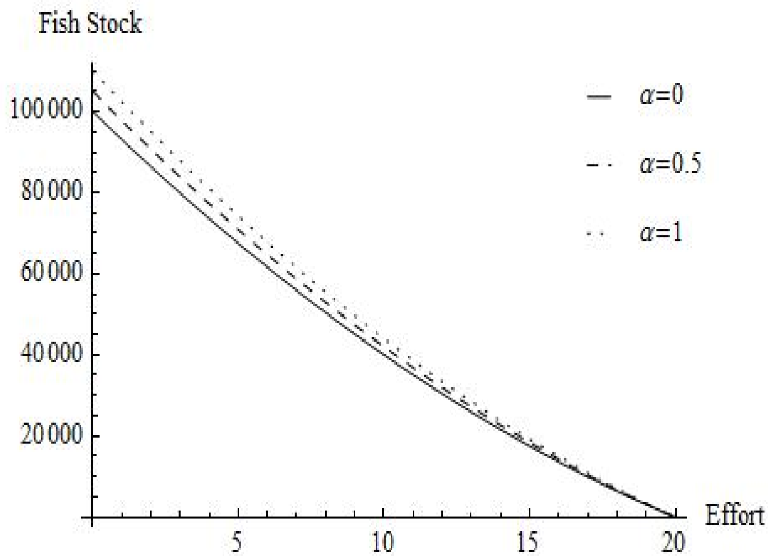

Figure 4: Fish stock as a function of effort for different values of α. The parameter values are $r = 0.1, q = 0.005, \tau = 0.05, \gamma = 0.001, K_{max} = 100000, \tilde{K} = 10000$.

4.4. Gear regulations and ARs as habitat conservation tools

Since the type of ARs we are interested in does not prevent further habitat degradation, gear regulations can be needed all the more that the use of destructive types of gear does not allow to fully benefit from the deployment of ARs, which also tend to be degraded. Suppose that the regulation of gear consists in the total prohibition of destructive gear, i.e. $\gamma = 0$ is imposed; the effort is fixed and exogenous. Two situations are possible in regard to this latter assumption: the exerted level of effort is the result of arrangements between local fishermen[6] or imposed by a local authority. But, in both cases, this level is not necessarily based on the considerations such as the MSY or the MEY, which can be, for example, due to the lack of information on the resource and costly data-gathering. We first compare the positive habitat effect of ARs with that of gear regulations and then investigate the performance of ARs with and without gear regulations.

[6]For instance, in the French Mediterranean, these arrangements are worked out by the institutions called "Prud'homie" that was developed many centuries ago by local fishermen who early became aware of the necessity of managing the resource.

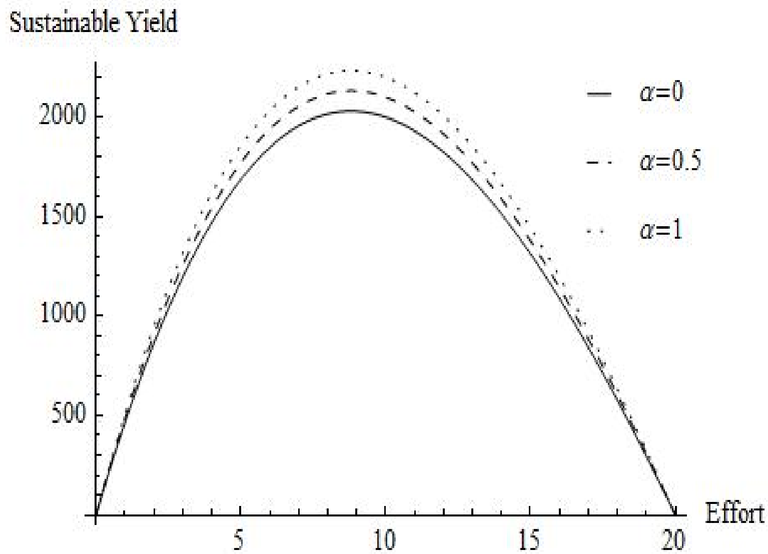

Figure 5: Sustainable yield as a function of effort for different values of α. The parameter values are $r = 0.1, q = 0.005, \tau = 0.05, \gamma = 0.001, K_{max} = 100000, \tilde{K} = 10000$.

Figures 7, 8 and 9 display fish stock, sustainable yield and sustainable rent as functions of effort for different sizes of ARs and compare them to those produced when carrying capacity is not reduced by fishing. As established for an open-access fishery, only for a sufficiently large AR project can the AR effect be greater than the negative habitat effect. This also holds for any level of effort. The only difference is the size of ARs required to exceed the negative habitat effect. Specifically, for a given effort E, the size $\alpha_{crit} = \frac{\gamma E/\tau}{\tilde{K}(1-\gamma E/\tau)}$ is required to produce a sustainable yield (rent) identical to the one obtained in the absence of both ARs and destructive fishing, which can be achieved by restricting the use of destructive gear ($\gamma = 0$). According to the expression found for α_{crit}, the higher the destruction parameter γ (the greater the negative habitat effect of fishing) is, the larger the size of ARs should be. In the same vein, the larger the effort exerted in the area, the larger this critical threshold. On the other hand, the more effective ARs are, i.e. the higher their contribution K' to carrying capacity is, the lower the AR size required to compensate the negative habitat effect of fishing.

Thus, for a given effort, the ban on destructive types of gear outperforms small-scale AR projects (lower than the threshold α_{crit}) when the objective is to improve

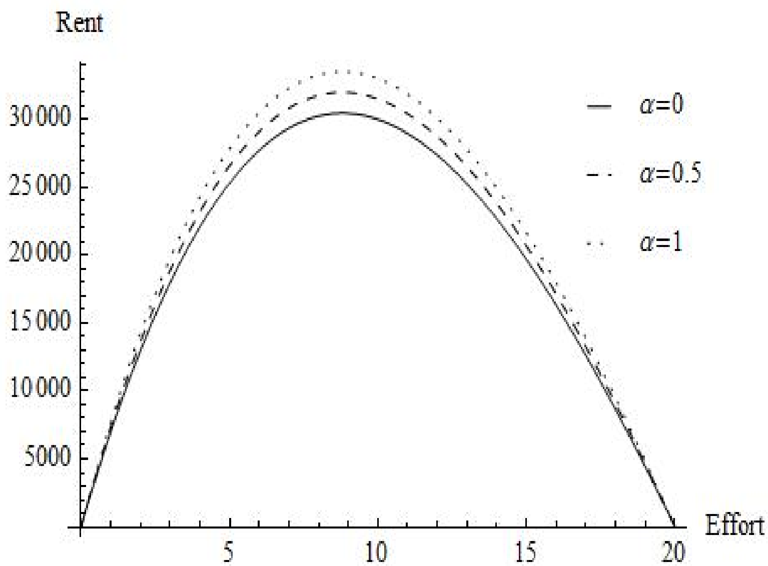

Figure 6: Sustainable rent as a function of effort for different values of α. The parameter values are $r = 0.1, q = 0.005, \tau = 0.05, \gamma = 0.001, K_{max} = 100000, \tilde{K} = 10000, p = 15, c = 0.1$.

the catches and the rent of the fishery by dealing with habitat degradation. However, by combining both management tools, even higher ecological and economic benefits can be yielded than expected from each tool separately (compare the dotted red curve to other curves in Figures 10, 11 and 12). Their combination is all the more advised as ARs alone are not able to extend the critical level of effort leading to fish extinction to the same level as in the absence of destructive harvesting even when a large AR project is implemented (compare the blue curves with the red normal curve).

4.5. Summary of results

To sum up the results of this section, two (intuitive) conditions have been identified under which the effects of ARs can be improved, that is, effort limitation (E_{MEY} or E_{MSY} depending on the objective) and gear restrictions (ban on any fishing activity that harms habitats).

The long-term reef performance in terms of fish stock, harvests and rent is summarized in Table I for the fisheries management regimes examined in this section. The performance scale ranges from 0, the worst performance, to 6, the best per-

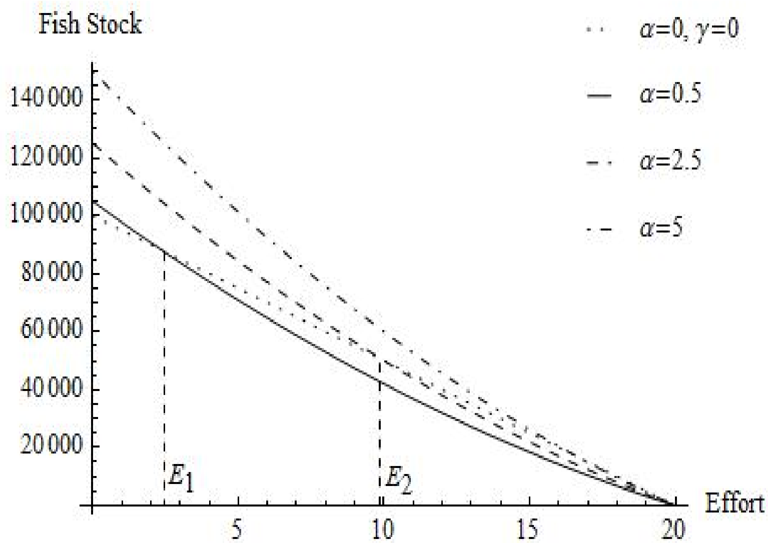

Figure 7: Fish stock under two settings: destructive ($\gamma > 0$) and habitat-friendly fishing ($\gamma = 0$). At the intersection of the dotted curve and other curves, we obtain the effort level at which the negative habitat effect is entirely compensated by ARs of a corresponding size. At E_1, the negative habitat effect is entirely compensated for $\alpha = 0.5$ while for $\alpha = 2.5$ and $\alpha = 5$ even greater benefits are produced than just offsetting the negative habitat effect. Similarly, at E_2, the negative habitat effect is entirely compensated for $\alpha = 2.5$ or higher. The parameter values are $r = 0.1, q = 0.005, \tau = 0.05, \gamma = 0.001, K_{max} = 100000, \tilde{K} = 10000$.

formance. By the worst long-term performance, we understand the dissipation of positive effects of ARs on a given indicator. Note that the scaling system established allows comparison between the regimes only for a given indicator and the relative comparison of the extent to which the indicators are improved is not provided in this table.

Table I: The performance of AR projects under the observed fisheries management regimes.

	Fish Stock			**Sustainable Yield**			**Sustainable Rent**		
Gear	E_{OA}	E_{MSY}	E_{MEY}	E_{OA}	E_{MSY}	E_{MEY}	E_{OA}	E_{MSY}	E_{MEY}
$\gamma > 0$	0	1	3	1	5	3	0	1	3
$\gamma = 0$	0	2	4	2	6	4	0	2	4

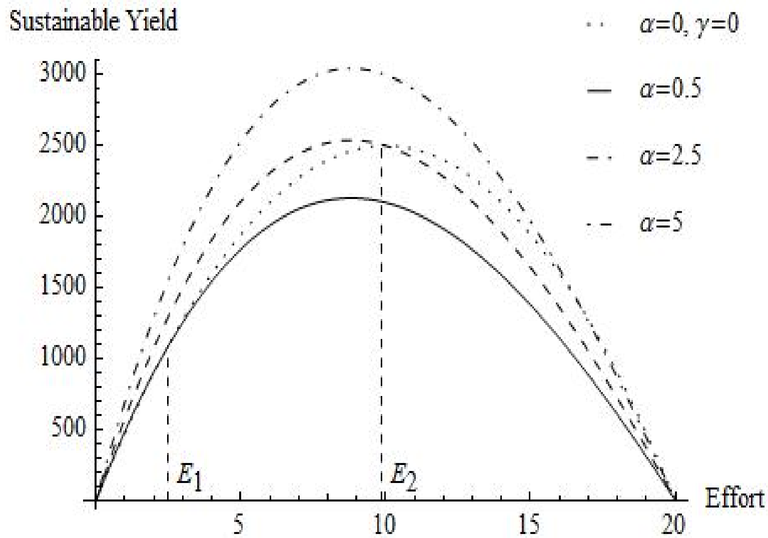

Figure 8: Sustainable yield under two settings: destructive ($\gamma > 0$) and habitat-friendly types of gear ($\gamma = 0$). At the intersection of the dotted curve and other curves, we obtain the effort level at which the negative habitat effect is entirely compensated by ARs of a corresponding size. At E_1, the negative habitat effect is entirely compensated for $\alpha = 0.5$ while for $\alpha = 2.5$ and $\alpha = 5$ even greater benefits are produced than just offsetting the negative habitat effect. Similarly, at E_2, the negative habitat effect is entirely compensated for $\alpha = 2.5$ or higher. The parameter values are $r = 0.1, q = 0.005, \tau = 0.05, \gamma = 0.001, K_{max} = 100000, \tilde{K} = 10000$.

5. Dynamically optimal fishing

In the previous sections, the present and future benefits were equally discounted, which is why the investment in an AR project assumed discrete in this study did not influence the results. In this section, we characterize the dynamically optimal harvesting and the AR strategy that maximize the expected present value of profit from harvest given that the present benefits have more weight for the fishery manager (or the society). To analyze this optimization problem, the cost function $C(\alpha)$ of AR project incurred at time 0 is introduced. We suppose that $C(\alpha)$ is convex and specify it as follows

$$C(\alpha) = d\alpha^{\omega}, \tag{17}$$

with $\omega \geq 1$.

According to this formulation, costly AR projects are expressed by high ω and d.

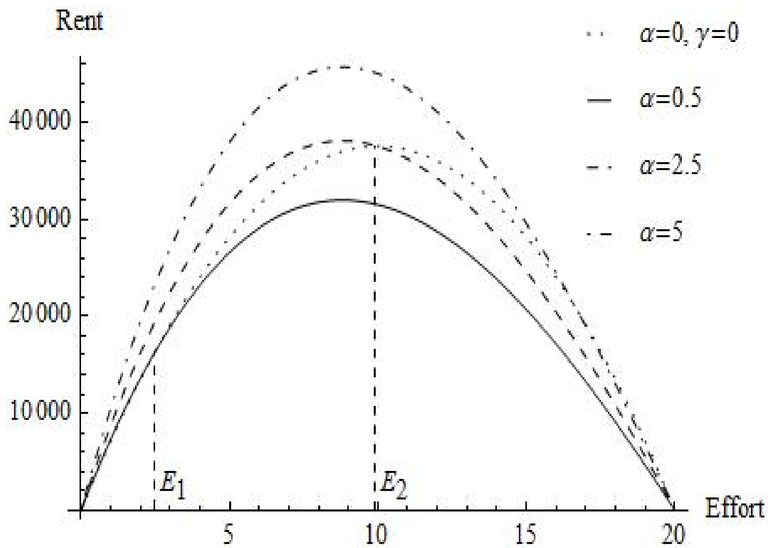

Figure 9: Sustainable rent under two settings: destructive ($\gamma > 0$) and habitat-friendly types of gear ($\gamma = 0$). At the intersection of the dotted curve and other curves, we obtain the effort level at which the negative habitat effect is entirely compensated by ARs of a corresponding size. At E_1, the negative habitat effect is entirely compensated for $\alpha = 0.5$ while for $\alpha = 2.5$ and $\alpha = 5$ even greater benefits are produced than just offsetting the negative habitat effect. Similarly, at E_2, the negative habitat effect is entirely compensated for $\alpha = 2.5$ or higher. The parameter values are $r = 0.1, q = 0.005, \tau = 0.05, \gamma = 0.001, K_{max} = 100000, \tilde{K} = 10000, p = 15, c = 0.1$.

To simplify the optimization problem and find an explicit analytical solution, we base this analysis on the model (9) where a strong assumption is adopted on the impact of fishing activities and ARs on carrying capacity.

Since the construction and the installation of ARs may be costly when the project is expected to produce a substantive effect on the marine environment, the problem of funding arises. To address this problem, three cases are examined. They vary in control variables, AR funding methods and model assumptions. In all three cases, the goal is to maximize the discounted rents of the fishery. The first case describes a situation where only one AR project can be implemented. It is put in place in the initial period of time. The project is financed from local government's budget and/or by voluntary efforts. The size of ARs cannot exceed some upper bound denoted here as α_{max}, the level which embodies technical and financial constraints. One policy variable is considered - the size α of ARs, $0 \leq \alpha \leq \alpha_{max}$. The effort is

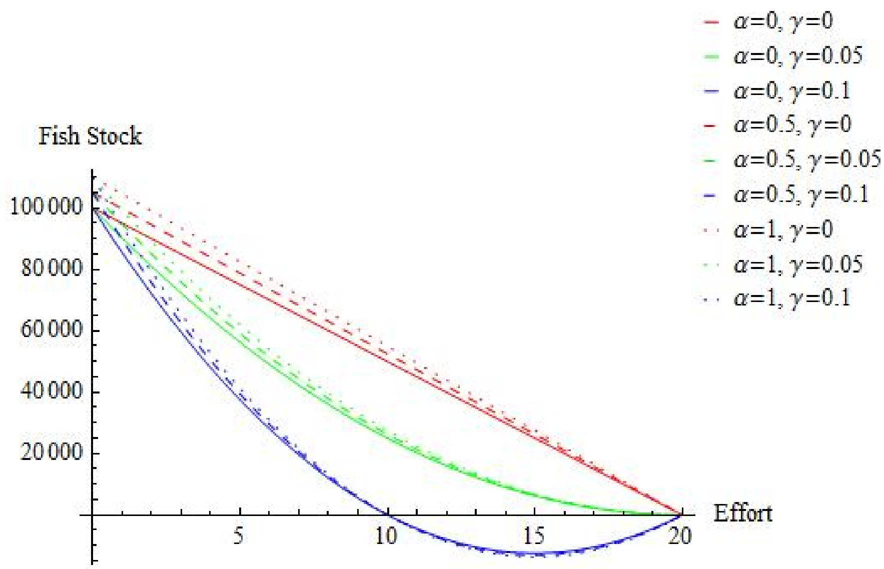

Figure 10: Fish stock for different combinations of γ and α. The red curves represent the behavior of the sustainable yield for $\gamma = 0$, the green curves for $\gamma = 0.05$ and the blue curves for $\gamma = 0.1$. The dotted curves correspond to $\alpha = 0$, the dashed curves to $\alpha = 0.5$ and the normal curves to $\alpha = 1$. For the highest considered value of habitat destruction parameter, $\gamma = 0.1$, $\frac{\tau}{\gamma}$ becomes inferior to $\frac{r}{q}$ and the critical effort reduces by falling from $\frac{r}{q}$ to $\frac{\tau}{\gamma}$. The parameter values are $r = 0.1, q = 0.005, \tau = 0.05, K_{max} = 100000, \tilde{K} = 10000$.

assumed fixed and exogenous. Second, one AR project is implemented and financed by the government but two policy variables are considered - the size α of ARs and the fishing effort E. A special case is analyzed here where the employed fishing gear is habitat-friendly, $\gamma = 0$. In the third case, the quantity of AR projects is not limited over time and subject to the amount collected from the taxes imposed on fishing landings. The burden of the realization of AR projects is therefore placed on the fishing units that operate in the area under consideration.

5.1. The case of a fixed and exogenous effort

Suppose that the overall effort exerted in the area is exogenous and constant over time. As explained earlier, this case is of interest because there are many examples of fisheries where the existing local institutional arrangements or the scarce information on the resource and marine ecosystem in general give little room for appropriate management of the inputs to the fishery such as the fishing effort ([14], [60], [61],

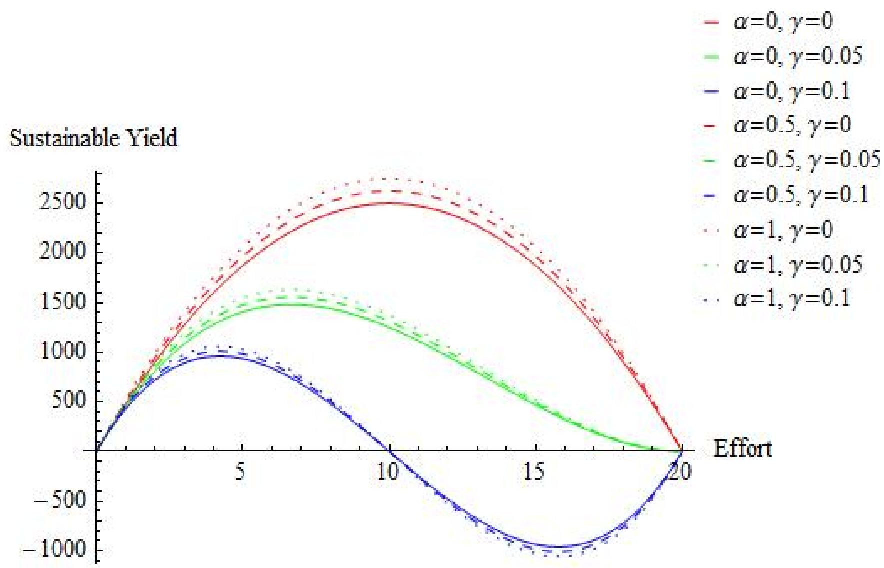

Figure 11: Sustainable yield for different combinations of γ and α. The red curves represent the behavior of the sustainable yield for $\gamma = 0$, the green curves for $\gamma = 0.05$ and the blue curves for $\gamma = 0.1$. The dotted curves correspond to $\alpha = 0$, the dashed curves to $\alpha = 0.5$ and the standard curves to $\alpha = 1$. For the highest considered value of habitat destruction parameter, $\gamma = 0.1$, $\frac{\tau}{\gamma}$ becomes inferior to $\frac{r}{q}$ and the critical effort reduces by falling from $\frac{r}{q}$ to $\frac{\tau}{\gamma}$. The parameter values are $r = 0.1, q = 0.005, \tau = 0.05, K_{max} = 100000, \tilde{K} = 10000$.

[58]). In light of this, we consider here a case where the only control variable is the AR size α. Because the AR project is implemented only once, this variable is constant over time. We assume that the expenses of an AR project are entirely borne by a local government in the period 0. There are no costs of management or other expenses related to the deployment of ARs beyond the period 0. The cost function for an AR project is assumed strictly convex.

Thus, the problem of optimal management is formally represented as

$$\underset{\alpha}{Max} V\{x, K, E, \alpha\} = \int_0^\infty e^{-\delta t}(pqEx - cE)dt - d\alpha^\omega \tag{18}$$

where α is the control variable, $0 \leq \alpha \leq \alpha_{max}$ and δ denotes the discount rate.

Since both the effort and the AR size are time-independent, 18 can easily be reduced to a static optimization problem. First, we find the expression for x by

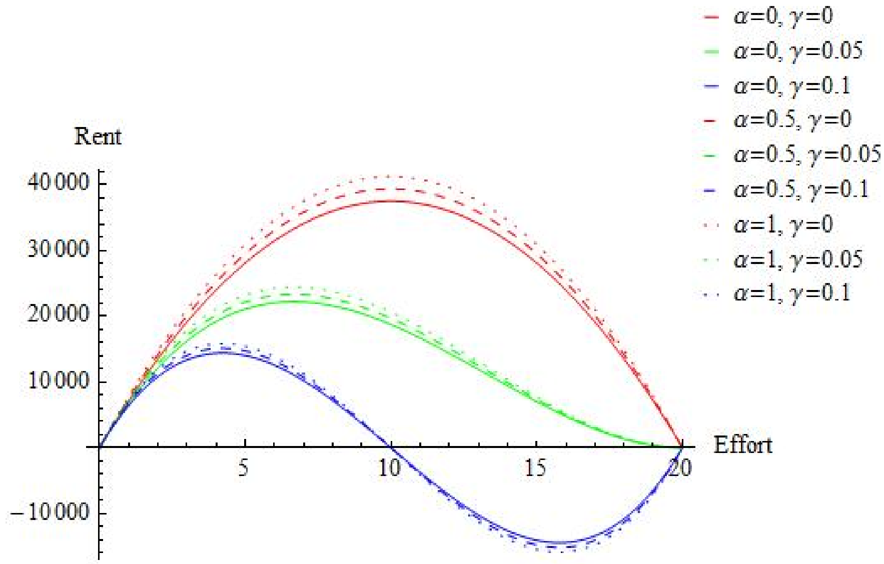

Figure 12: Sustainable rent for different combinations of γ and α. The red curves represent the behavior of the sustainable yield for $\gamma = 0$, the green curves for $\gamma = 0.05$ and the blue curves for $\gamma = 0.1$. The dotted curves correspond to $\alpha = 0$, the dashed curves to $\alpha = 0.5$ and the standard curves to $\alpha = 1$. For the highest considered value of habitat destruction parameter, $\gamma = 0.1$, $\frac{\tau}{\gamma}$ becomes inferior to $\frac{r}{q}$ and the critical effort reduces by falling from $\frac{r}{q}$ to $\frac{\tau}{\gamma}$. The parameter values are $r = 0.1, q = 0.005, \tau = 0.05, K_{max} = 100000, \tilde{K} = 10000, p = 15, c = 0.1$.

solving differential equation (9):

$$x = (K_{max} + \alpha\tilde{K})\left(1 - \frac{qE}{r}\right)(1 - \theta E). \tag{19}$$

Then we substitute (19) into the objective integral (18) and solve it:

$$\underset{\alpha}{Max} V\{x, K, E, \alpha\} = \frac{1}{\delta} pqE\left((K_{max} + \alpha\tilde{K})\left(1 - \frac{qE}{r}\right)(1 - \theta E) - \frac{c}{pq}\right) - d\alpha^{\omega}. \tag{20}$$

After some basic calculations, we obtain

$$\alpha^* = \sqrt[\omega-1]{\frac{\tilde{K}pqE(1 - qE/r)(1 - \theta E)}{\delta d\omega}}, \tag{21}$$

where $\omega > 1$.

The optimal size α^* is positively related to $\tilde{K}$, p, r and negatively related to δ,

θ, ω, d, i.e. $\frac{\partial \alpha^*}{\partial \tilde{K}} > 0$, $\frac{\partial \alpha^*}{\partial p} > 0$, $\frac{\partial \alpha^*}{\partial r} > 0$ and $\frac{\partial \alpha^*}{\partial \delta} < 0$, $\frac{\partial \alpha^*}{\partial \theta} < 0$, $\frac{\partial \alpha^*}{\partial \omega} < 0$, $\frac{\partial \alpha^*}{\partial d} < 0$. As for the relations to the effort E and the catchability coefficient q, they are not monotonic:

$\frac{\partial \alpha^*}{\partial E} > 0$ if $E < \frac{1}{3}\left(\frac{r}{q} + \frac{1}{\theta} - \sqrt{\frac{r^2}{q^2} - \frac{r}{\theta q} + \frac{1}{\theta^2}}\right)$, $\frac{\partial \alpha^*}{\partial E} \leq 0$ otherwise;
$\frac{\partial \alpha^*}{\partial q} > 0$ if $E < \frac{r}{2q}$, $\frac{\partial \alpha^*}{\partial q} \leq 0$ otherwise.

The positive relations are intuitive. When the target fish is highly priced, fishery manager with objective (18) is motivated to provide better conditions for its growth by implementing a large AR project. In the same vein, the faster the fish grows (high r), the faster the fish stock approaches the carrying capacity level and the more interesting it is to extend this level, which, in our case, can be done through the deployment of ARs. Further, if highly efficient types of ARs in terms of their contribution $\tilde{K}$ in carrying capacity can be designed and constructed without increase in the cost $C(\alpha)$, the AR policy will represent a more significant economic interest for fishery managers.

Negative relations to d, ω, θ and δ are not surprising either. The larger the investments required for the implementation of an AR project (high d or/and ω), the lower its cost-effectiveness and, thereby, the smaller the project should be (see Figure 13). Similarly, a highly discounting fishery manager is less motivated in AR projects as compared to a low discounting manager since they involve prior investments and the gains from ARs are not immediate. In the extreme case when $\delta \to \infty$, ARs as a fisheries management option will not win through, i.e. $\alpha^* = 0$. On the contrary, if $\delta \to 0$, the maximal possible amount of ARs should be deployed, i.e. $\alpha^* = \alpha_{max}$. Finally, when highly destructive fishing practices and techniques are employed in the area, the benefits of ARs are jeopardized and can even disappear, which is why AR policy loses its utility with increasing θ. It can then be recommended to undertake some prior measures to reduce the damages inflicted upon habitats in the concerned area.

Further, the non-monotonic relation to q can also be easily interpreted. Since, at high efforts, more fishes are extracted before they can reproduce and contribute to the population growth, increase in carrying capacity (limiting population growth) reached through deployment of ARs has less and less sense as the extraction capacity q of fishing units increases.

Finally, the most interesting relation is with E. Two setups are distinguished here with respect to the fishing pressure: moderately and heavily exploited fisheries (see Figure 13). In a moderately exploited fishery, the higher the effort is, the higher the size of ARs should be. In a heavily exploited fishery, the opposite is true. From this it follows that, under too high or too low fishing pressure, ARs are of little use while the best results from AR deployment (α^* is maximized) are expected at the effort $\tilde{E} = \frac{1}{3}\left(\frac{r}{q} + \frac{1}{\theta} - \sqrt{\frac{r^2}{q^2} - \frac{r}{\theta q} + \frac{1}{\theta^2}}\right)$. The higher the ratios $\frac{r}{q}$ and $\frac{1}{\theta}$, the higher this level of effort. Thus, in highly productive and respectful fisheries, ARs are still capable of providing significant economic benefits even at high efforts.

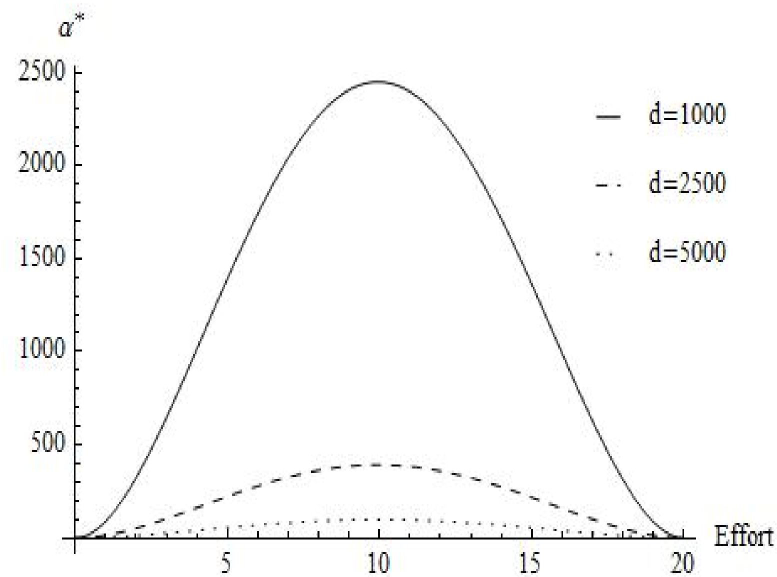

Figure 13: The optimal AR size α^* as a function of effort for different values of the AR cost d. The parameter values are $r = 0.1, q = 0.005, \tau = 0.05, \gamma = 0.001, K_{max} = 100000, \tilde{K} = 10000, p = 15, c = 0.1, \delta = 0.05, \omega = 1.5$.

5.2. Special case: habitat-friendly fishing

Suppose now that the fishery manager has absolute control over the level of fishing effort. The discounted rents of the fishery can then be maximized over both fishing effort and the size of ARs. An explicit solution to this problem is derived for a special case where the destruction parameter $\theta = 0$ implying the use of habitat-friendly fishing gear. We also suppose that the cost of the deployment of ARs is linear to α, i.e. $\omega = 1$. We still assume that the local government bears all the expenses related to AR deployment.

Thus, we solve the following problem

$$\underset{\alpha,E}{Max} V\{x,K,E,\alpha\} = \int_0^\infty e^{-\delta t}(pqEx - cE)dt - d\alpha \tag{22}$$

subject to the state equation

$$\dot{x} = rx\left(1 - \frac{x}{K_{max} + \alpha\tilde{K}}\right) - qEx, \tag{23}$$

$$x(0) = x_0,$$

where α and E are two control variables, $0 \leq \alpha \leq \alpha_{max}$, $0 \leq E \leq E_{max}$.

According to the Pontryagin maximum principle, we build a Hamiltonian of the problem

$$\mathcal{H}(x,t,E,\lambda) = pqEx - cE - \delta d\alpha + \lambda\left(rx\left(1 - \frac{x}{K_{max} + \alpha\tilde{K}}\right) - qEx\right), \tag{24}$$

where $\lambda(t)$ is known as the shadow price of fish.

The term $\delta d\alpha$ defines a financial cost, or opportunity cost, associated with the implementation of the AR policy, i.e. potential returns from the monetary sum invested in ARs if it were invested in an alternative activity.

The necessary optimality conditions are as follows:

$$\dot{\lambda} = \delta\lambda - \frac{\partial\mathcal{H}}{\partial x} = \delta\lambda - pqE - \lambda\left(r - \frac{2rx}{K_{max} + \alpha\tilde{K}} - qE\right); \tag{25}$$

$$\frac{\partial\mathcal{H}}{\partial\alpha} = -\delta d + \lambda\frac{r\tilde{K}x^2}{(K_{max} + \alpha\tilde{K})^2}; \tag{26}$$

$$\frac{\partial\mathcal{H}}{\partial E} = pqx - c - \lambda qx. \tag{27}$$

The resource should be fished as intensively as possible when $\frac{\partial\mathcal{H}}{\partial E} > 0$, i.e. $E^* = E_{max}$; while $\frac{\partial\mathcal{H}}{\partial E} < 0$, no fishing should take place; if $\frac{\partial\mathcal{H}}{\partial E} = 0$, the effort should be set to its interior value E^*.

Since the control α is constant over time throughout all periods, it should be set to the level α^* found from the equation $\frac{\partial \mathcal{H}}{\partial \alpha} = 0$ whatever the sign of $\frac{\partial \mathcal{H}}{\partial \alpha}$.

By solving this system, we find that the equation for the optimal level of stock x^* is algebraic and thus $\dot{\lambda} = 0$. Equation (26) is not dependent on α:

$$\frac{\partial \mathcal{H}}{\partial \alpha} = -\delta d + \frac{pqr\tilde{K}E(1-qE/r)^2}{\delta + r - qE}, \tag{28}$$

which means that the optimal level α^* is on the extremes, either 0 or α_{max}. By solving $\frac{\partial \mathcal{H}}{\partial \alpha} = 0$ with respect to E, we find that this cubic equation can have up to three distinct positive real roots depending on the model parameters. Since the constant of the corresponding polynomial is negative and the leading coefficient is positive, there is at least one positive real root:

$$E^* = \frac{q^3}{6}\left(4rq^2 + \frac{2^{4/3}rq^4(pr\tilde{K} - 3d\delta)}{A} + \frac{2^{4/3}A}{p\tilde{K}}\right) \tag{29}$$

with $A = \Big(-2p^3r^3q^6\tilde{K}^3 + 9dp^2q^6r\delta\tilde{K}^2(r+3\delta) +$
$+3\sqrt{3}\sqrt{dp^3q^{12}r^2\delta^2\tilde{K}^3\left(-4p^2r^2\tilde{K}^2 + 4d^2r\delta + dp\tilde{K}(-r^2 + 18r\delta + 27\delta^2)\right)}\Big)^{1/3}$.

If there are three distinct positive real roots, then the optimal level α^* is determined as follows (Figure 14). Between 0 and the first root E_1, the AR size $\alpha^* = 0$; between E_1 and E_2, $\alpha^* = \alpha_{max}$; between E_2 and E_3, $\alpha^* = 0$; for the efforts higher than E_3 the optimal level $\alpha^* = \alpha_{max}$. If there are no more than two roots, then between 0 and E_1, $\alpha^* = 0$ while for the effort higher than E_1, $\alpha^* = \alpha_{max}$.

Thus, it is the effort obtained from equation $\frac{\partial \mathcal{H}}{\partial E} = 0$ that will determine which extreme 0 or α_{max} is optimal. To find the optimal effort, we equalize $\frac{\partial \mathcal{H}}{\partial E}$ to zero and substitute two extremes for α into the equation:

$$\frac{2q^2}{r}E^2 - \left(\frac{\delta}{r} + 3 - \frac{c}{pq(K_{max} + \alpha^*\tilde{K})}\right)qE + (\delta + r)\left(1 - \frac{c}{pq(K_{max} + \alpha^*\tilde{K})}\right) = 0. \tag{30}$$

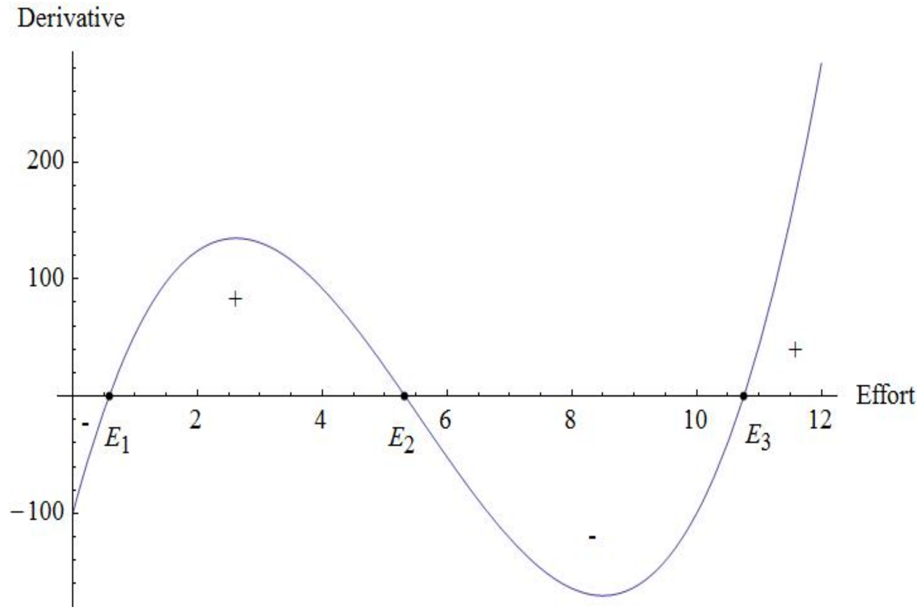

Figure 14: This schematic graph represents the behavior of $\frac{\partial \mathcal{H}}{\partial \alpha}$.

There are two solutions for equation (30)

$$E_1^* = \frac{3r}{4q} + \frac{r}{4q}\left(\frac{\delta}{r} - \frac{c}{pq(K_{max} + \alpha^* \tilde{K})}\right) -$$

$$-\sqrt{\left(\frac{3r}{4q} + \frac{r}{4q}\left(\frac{\delta}{r} - \frac{c}{pq(K_{max}+\alpha^* \tilde{K})}\right)\right)^2 - \frac{r^2}{2q^2} - \frac{r\delta}{2q^2} + \frac{cr(r+\delta)}{2pq^3(K_{max}+\alpha^* \tilde{K})}}; (\textbf{??})(31)$$

$$E_2^* = \frac{3r}{4q} + \frac{r}{4q}\left(\frac{\delta}{r} - \frac{c}{pq(K_{max} + \alpha^* \alpha^* \tilde{K})}\right) +$$

$$+\sqrt{\left(\frac{3r}{4q} + \frac{r}{4q}\left(\frac{\delta}{r} - \frac{c}{pq(K_{max}+\alpha \tilde{K})}\right)\right)^2 - \frac{r^2}{2q^2} - \frac{r\delta}{2q^2} + \frac{cr(r+\delta)}{2pq^3(K_{max}+\alpha \tilde{K})}}.(32)$$

Both solutions are distinct since the discriminant is strictly positive. It can also be shown that E_1^* belongs to the domain of acceptable values. According to Figure 15, the maximum is achieved at E_1^*. Let us further denote the optimal effort as E^*. We compare E^* to the roots obtained from (28) by setting α^* first to 0, then to α_{max}. If $E^* < E_1^*$ and E^* was found by setting α^* to 0, then E^* is a solution of the system of equations (25)-(27) and α^* is indeed equal to 0. Similarly, if $E_1^* < E^* < E_2^*$ and E^* was found by setting α^* to α_{max}, then $\alpha^* = \alpha_{max}$; if $E_2^* < E^* < E_3^*$ and E^* was found by setting α^* to 0, then $\alpha^* = 0$; finally, if $E^* > E_3^*$ and E^* was found by setting α^* to α_{max}, then $\alpha^* = \alpha_{max}$. When there are no more than two distinct roots for (28), there is at least one acceptable effort that is the solution of (25)-(27). In the case of three roots, there are certain sets of model parameters at which it is optimal not to fish and, therefore, not to deploy ARs.

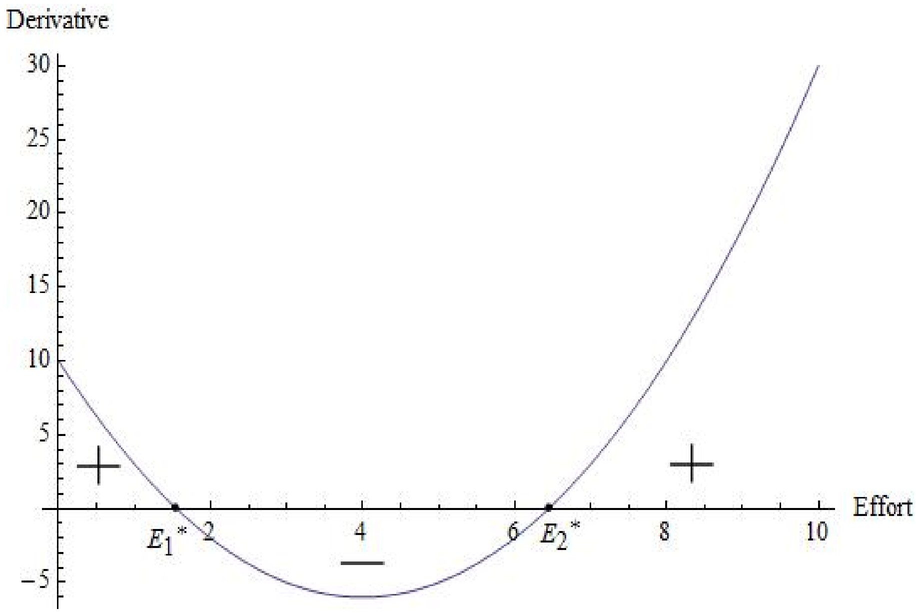

Figure 15: This schematic graph represents the behavior of $\frac{\partial \mathcal{H}}{\partial E}$.

It can be shown that the optimal effort E^* is negatively related to c and positively related to α_{max} whereas the roots of equation (28) are not dependent on these parameters. Thus, one property of the optimal solution is straightforward. For c and α_{max} sufficiently large, the discounted rents of fishery resulting from the deployment of the maximal amount α_{max} of ARs are higher than those yielded without ARs provided that the AR cost d and the discount rate δ are sufficiently low. This holds for all three cases explained above (one, two or three distinct roots).

This is in line with the observations of real-world fisheries where ARs are regarded as a means to increase the efficiency of fishermen, the reason for which such projects gain support from local fishing communities. ARs are commonly immersed in the areas with poor habitats. In such environments the biological conditions in which fish populations reproduce are poor and the cost of fishing is high. The fish is difficult to catch and a longer search period is required implying higher fuel expenditures, more wasted bait and labor. By enhancing fish populations and aggregating them, ARs lower the cost of fishing. This is why costly fisheries are more in need of such projects.

For a one-dimensional dynamic problem, it is the most rapid approach path that is optimal for achieving the interior solution ([52]). According to it, the optimal path to the obtained interior solution is as follows. As long as $x < x^*$, no fishing should take place; if, on the contrary, $x > x^*$, the fishing effort should be set to its maximum E_{max}; otherwise, to the interior solution $E = E^*$.

In other words, in the period 0, ARs of the size α^* should be immersed and a temporary reserve should be established if the target fish population is below the optimal level. Normally, the option of AR deployment is contemplated when the target fish population in the area under consideration needs to undergo significant recovery. That is why it is reasonable to assume that the initial stock $x(0) < x^*$. The creation of a temporary reserve is then inevitable and allows ARs to be colonized by fish in order to achieve this optimal level. The lower the initial population, the longer the reserve will be in place. Therefore, the existing tendency (for example, in the French Mediterranean) to impose temporary bans on fishing activities in AR areas is consistent with the optimal path.

5.3. Catch royalties as a means for AR funding

As discussed in section 2.4, in most cases, financial costs associated with the implementation of AR projects are covered by government grants and voluntary efforts. Suppose now that the fishery manager has the possibility to fund AR projects through imposing a landings tax referred to as the catch royalties by Clark [52]. An alternative to catch royalties put forward in the fisheries economics literature is effort royalties. However, since, as noted by Clark [52], it is easier to cheat on the effort level than on the catches and annual effort may be more difficult to assess, we do not consider this option. We assume that the tax is collected at each period of time and is entirely spent to build and install ARs. Here it is supposed that the fishery manager does not make efforts to obtain government's help allowing to immediately achieve the optimal AR size through the implementation of one large AR project but instead realizes a number of small projects distributed over time using the collected taxes. Each period of time additional ARs are deployed as long as a non null tax is collected leading to a continuous increase of the carrying capacity of the area. Given this funding system, we look for the optimal tax rate.

The problem that fishery manager solves is

$$\underset{T,E}{Max} V\{x, K, E, \alpha\} = \int_0^\infty e^{-\delta t}((p-T)qEx - cE)dt \tag{33}$$

subject to the state equation

$$\dot{x} = rx\left(1 - \frac{x}{K_{max} + L\tilde{K}}\right) - qEx, \tag{34}$$

$$\dot{L} = \frac{TqEx}{d}, \tag{35}$$

$$x(0) = x_0,$$

where $L(t)$ is the overall size of the ARs deployed until time t, $T(t)$ is the tax on fish landings at time t, d is the cost per reef unit.

We treat T as the control variable and wish to determine a tax policy $T = T(t)$, $0 \leq T(t) \leq T_{max}$. Another variable that is controlled by the fishery manager is the fishing effort $E = E(t)$, $0 \leq E \leq E_{max}$.

$\tilde{K}L(t)$ is the artificially produced overall increase of carrying capacity up to time t due to the deployments of ARs. The quantity $T(t)qE(t)x(t)$ is the monetary sum collected at time t and used for the implementation of an AR project of the size $L(t + \Delta t) - L(t)$.

In fact, we obtain an optimization problem that is equivalent to the previous one (22)-(23) in terms of optimal levels. According to the results yielded for maximization problem (33)-(35), the optimal tax rate is chosen so as to satisfy the most rapid approach path, i.e. $T = T_{max}$ as long as $L < L^*$ where $L^* = \alpha^*$.

In this case, it is difficult to find the most rapid approach path to the optimal values. One possible path to approach them from some initial population level $x(0)$, which is not necessarily optimal, is to set E to its interior value E^*, starting from period 0, and impose the maximal possible tax, $T = T_{max}$, until the total size of ARs is sufficient to drive the carrying capacity level to L^*. Putting the tax to its maximal level is necessary to accelerate as much as possible the convergence to L^*. If the fish stock x is still inferior to its optimal value x^* when L^* is reached, fishing can be temporarily forbidden so as the fish stock x approaches x^* more quickly. As soon as $x = x^*$, the ban is lifted and the effort is again set to E^*. Now what if we reverse the order of management measures? First, a temporary reserve is created in the area until x converges $x = x^*$ and then the area is opened to fishing, the effort is set to E^* and AR projects are carried out until L reaches L^*. In the last sequence of measures, the fish stock increases and moves away from the optimal value. To return to it as fast as possible, the effort should be set to its maximal value and, when $x = x^*$, it is again set to E^*. However, this second path is technically less coherent than the first one. The optimal level of stock x^* may not be reached if ARs are not immersed before the reserve is established. Moreover, from practical point of view, it seems more appropriate to first deploy ARs and then create a reserve to favor the colonization of ARs by marine organisms.

The first approach path is displayed in Figures 16 and 17. This case is one of possible settings where the optimal level of fish stock $x^* = 1031$ cannot be achieved without the implementation of ARs since this level is higher than the carrying capacity K_{max} before ARs are deployed. We also witness here a case where a temporary ban on fishing activities is necessary to ensure faster convergence to the optimal levels.

Since the optimal approach path for achieving the interior solution is the most rapid approach path, the AR funding method allowing an investment that is sufficiently large to deploy the optimal size of ARs at once outperforms in terms of time the investment strategies of a smaller scale. That being said, when in the need of a large amount of ARs to achieve the optimal levels, it is more likely that the government is a better investor than fishermen contributing to AR projects through taxes on fish landings. However, too large investment may be too demanding for local budget. Thus, when deciding on an optimal investment strategy in ARs, a trade-off should be made between the opportunity costs of paying the whole sum for the deployment of the required size of ARs at once and the foregone benefits due to

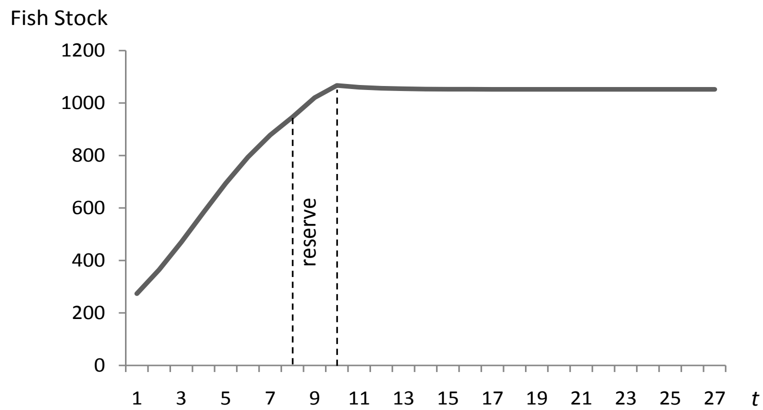

Figure 16: This graph represents the intertemporary behavior of fish stock when, starting from $t = 0$, the effort is set to the optimal level E^* and the tax rate is set to its maximal value T_{max} until the optimal size of ARs α^* is reached. At $t = 9$, α^* is reached and a reserve is established. At $t = 11$, when the optimal stock level is reached, the ban on fishing is lifted and no further tax is imposed. The parameter values are as follows: $r = 0.5$, $K_{max} = 1000$, $\tilde{K} = 1000$, $q = 0,005$, $T_{max} = 0,001$, $x(0) = 200$, $p = 15$, $\delta = 0.1$, $c = 73$, $d = 1000$, $\alpha_{max} = 0.1$, $x^* = 1031$, $E^* = 6.3$.

dividing one-shot AR project of optimal size into a number of small projects, thus delaying the convergence to the optimal levels.

There is also another point. If catch royalties are chosen as the source for AR investments, equity issue arises when the entry to the fishery is not regulated and outsiders can operate in the AR area. The fishermen who arrive after the optimal amount of ARs is deployed are not demanded to pay royalties but still benefit from the presence of ARs. In small-scale fisheries, this issue is less accentuated because the local fishermen prevent outsiders from entering the fishery ([58]).

6. Discussion and conclusion

In the present paper, we attempt to provide a thorough and wide analysis regarding the most important management issues that AR policy raises. The model developed in our earlier work and slightly adapted to take account of the positive habitat effect of ARs gives new insights into their potential to improve the economic

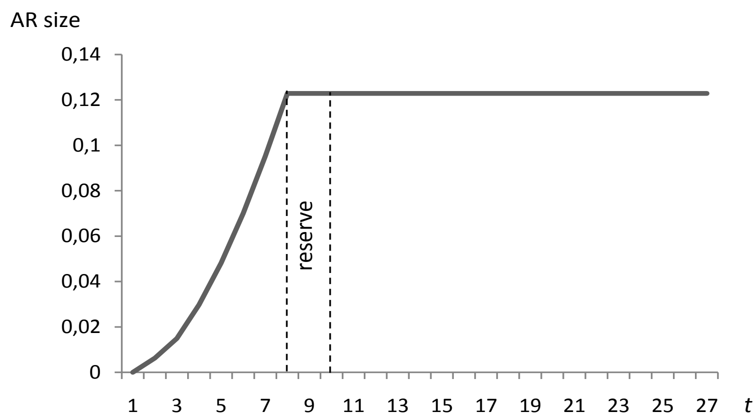

Figure 17: This graph represents the intertemporary behavior of AR size when, starting from $t = 0$, the effort is set to the optimal level E^* and the tax rate T is set to its maximal value until the optimal AR size α^* is reached. At $t = 9$, α^* is reached and a reserve is established. At $t = 11$, when the optimal stock level is reached, the ban on fishing is lifted and no further tax is imposed. The parameter values are as follows: $r = 0.5$, $K_{max} = 1000$, $\tilde{K} = 1000$, $q = 0,005$, $T_{max} = 0,001$, $x(0) = 200$, $p = 15$, $\delta = 0.1$, $c = 73$, $d = 1000$, $\alpha_{max} = 0.1$, $x^* = 1031$, $E^* = 6.3$.

performance of the fishery. We believe that this model may serve as a reference for future AR projects.

The main advantage of the chosen modeling solution is that it provides more accurate analysis through the examination of the interplay between the positive habitat effect of ARs and the negative habitat effect of fishing, neglected in conventional models. This interplay is important because, one of the main purposes of ARs being the recovery of marine ecosystems, they offset the negative habitat effect caused by destructive fishing.

The economic analysis based on our model supports the studies that accentuate the need for the on-going management of AR projects. We underline two main management measures necessary for the success of AR projects, area closures and effort limitation.

Most of the existing biological studies and surveys are too optimistic about the performance of ARs as they convey their short-term benefits. However, as soon as the economic incentives come into play, we show that these benefits decimate if no management is afforded to ARs. Our analysis clearly shows that, in an unregulated open-access fishery, the deployment of ARs leads to the increase of effort in the long term. While a temporary raise in fish stock and rents of the fishery is followed by a decline until the open-access level, which is the same as in the absence of ARs, one positive effect still remains, that is the catches are increased in the long term. We find that, combined with gear regulations and effort restrictions, ARs are able to yield significant economic benefits relative to an unregulated open-access regime. Gear regulations are important since the reef units, in which we are interested, are not able to deal with habitat degradation induced by destructive fishing. They are only a temporary solution for habitat loss mitigation and the positive habitat effect they produce may not last for long if a proper management plan is not carried out. However, according to our model, when the fishing techniques employed in the fishery are not too harmful, the AR size can be tuned so as to deal with the negative effects of the habitat loss caused by these techniques on the catches. In the same vein, the implementation of effort limitation wards off the build-up of fishing pressure shown to occur when the fishing activities in the AR area are not regulated. Yet, not only under too high but also too low fishing pressure, ARs yield little economic benefit in both static and dynamic settings. It is hence not economically relevant to implement ARs in underexploited fisheries either.

In a dynamic framework, by examining the case where fishery manager has a total control over the fishing effort and the AR size, we find that setting up a temporary area closure allows the optimal equilibrium level of fish stock dependent, among other things, on the AR size to be reached in an optimal way. In other words, ARs should be allowed to be colonized by marine organisms in order to follow the optimal path. Thus, fishery managers who put in place temporary area closure for this reason (for instance, in the French Mediterranean [62], [63]) may be able to follow the optimal path on condition that a proper subsequent control of fishing effort is ensured.

A solution to the problem of funding, analyzed in a dynamic context, is proposed. The implementation of one-shot optimal AR project may demand too large investment to satisfy the financial constraints of local government. In that case, this project may be divided into a number of small AR projects and be financed by catch royalties collected each period of time and entirely invested in AR projects. According to the optimal solution, the royalties should be set to their maximal rate and collected until the optimal equilibrium surplus of carrying capacity is reached.

The framework elaborated in this study creates a basis for the further analysis of ARs. Some assumptions can be relaxed. For instance, instead of considering effort as a constant and exogenous parameter, it can be modeled as endogenous dynamic variable dependent on the rent produced by the resource ([57]). In that case, effort will gradually increase when the rent is positive and decrease when it is negative. Further, the migration of effort may be considered depending on the relative profitability of the areas ([13]). This can allow addressing the problem of the build-up of effort in the AR area in a dynamic framework. Other possible worthwhile extensions may involve the incorporation of the concentration effect of ARs ([50]) as well as on-going management costs. Finally, a multi-species setting may be able to provide a more accurate analysis since ARs have a wider impact on the ecosystem and the biodiversity of the area than assumed in this study.

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