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Spillover from marine protected areas on the pacific coast in Colombia: A bioeconomic modelling approach for shrimp fisheries

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ABSTRACT

Marine protected areas are currently recognized as an alternative for the conservation of marine ecosystems. Although the protection reduces the area available for fishing, it has been argued that the spillover effect can increase resources in the adjoining areas. The purpose of this study is to calculate the value of the provision of fishing resources resulting from an increase in the system of marine protected areas in Colombia. To do that, a surplus-production based dynamic bio-economic model is developed for white shrimp (Litopenaeus occidentalis), a species important socially and economically in Colombia. The model includes a protected area with essential habitats, a nonprotected area, and mobility of species between them. Changes in biomass, catch, effort and the economic benefits of fishing through time, under different protection scenarios, are analyzed. Despite the reduction of the area available for fishing, in the mid-term, the protected areas generate increased levels of biomass and greater benefits associated to the fishing activity, because of the spillover effect. In that sense, the marine protected areas constitute a valid alternative for fishery conservation with the potential to generate economic benefits in the midterm.

1. Introduction

Marine ecosystems are characterized by their complexity, high biodiversity and provision of important ecosystem services for human communities, where fishing has a significant role [10,32,40]. Fisheries provide direct employment to about 200 million people and account for 17% of the total human consumption of animal protein [15]. However, marine ecosystems are losing their ability to provide their services, and the income of the people who depend on these provision services are diminishing, as there are increasingly fewer resources available [14].

The establishment of marine protected areas has been one of the main strategies to protect the natural ecosystems and the services they provide, through areas to protect spawning stocks, juvenile fish or sensitive habitats [39,41]. A protected area is defined as a geographic area in which access to the resources provided by the ecosystems is either regulated or prohibited. There can be different degrees of regulation, ranging from establishing limit catch rates, prohibiting the use of harmful fishing techniques, up to, in some cases, forbidding access to some areas. When these areas are intangible they are known as marine reserves, defined as "an area of the ocean that is completely protected from the extraction of animals and plants and the alteration of habitats, except for those required for scientific monitoring" [31].

Currently, Colombia has 16 (three added in the last few years) marine protected areas (MPAs) that belong to the National System of Protected Areas (SINAP acronym in Spanish), which represent about two percent of the country's marine surface. Given this scenario, and as documented by INVEMAR, UAESPNN & TNC [23], there are still conservation goals to be fulfilled, which could contribute to overcome the problem of loss of ecosystems and the services they provide, as is the case of overfishing in Colombia. Indeed, catch rates in Colombia have dropped in recent years to less than 20% of their historic maximum levels in the Pacific (120,000 t) and Caribbean (25.000 t) in the late 90 s [33]. Specifically, stock assessment of the white shrimp in the Colombian Pacific have categorized this resource as depleted [34]. Many fisheries are unsustainable as the benefits derived from the activity are not greater than the costs incurred by the fishermen [11].

Over exploitation of marine resources can be explained by the fact that fisheries are common pool resources and, therefore, characterized by high exclusion costs, and high rivalry [30]. Consequently, each agent that may benefit from fishing resources will do so without considering the cost of extraction on the rest of the fleet, and will end up overfishing and depleting the resource, a phenomenon that Hardin [20] called the tragedy of the commons. The agents, to maximize their own profits, appropriate the largest amount of the resources possible and added

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together lead to an equilibrium whereby the individual and total benefits are lower than what they could be in other scenarios or equilibriums.

Insofar as the valuation of the fishing activity, the marine and coastal ecosystems offer at least two types of services: i) provisioning services (direct use value): in situ catch and extraction of fish and other species to be consumed or as a source of income; ii) support services (indirect use value): habitats and breeding centers for commercial species captured in situ or offshore by industrial or artisanal fishermen. The value of the support services is derived from sustaining and protecting economic activities (such as fisheries) that have values that can be measured directly [8]. In this way, the indirect-use value of the support services is related to the changes in the value of production or consumption of the activity that it is protecting or "supporting". However, given that this contribution does not have a market and relates only indirectly with economic activities, these indirect use values are difficult to measure [5]. Approximations to these indirect use values have been based mainly on estimating the relationships between the existence of the ecosystems and fishing production within or outside of the area [8]. The provision of these services is associated mainly to mangrove ecosystems, seagrasses, estuaries and coral reefs.

To approximate these values, over the years, predictive models based on biological and economic variables have been proposed, to understand the dynamics of the fishing activity considering the economic benefits that they generate and the biological populations on which they depend [2]. Extensions of these bio-economic models have been applied to include MPAs [24], but these are mainly theoretical and not many studies have been applied to any particular fishery. The protection of a MPA allows the populations within the area to grow more quickly than those outside, where they are harvested. The upper limit of this increase in the populations within the MPAs is the carrying capacity of the ecosystem [42], whereby the population cannot grow any more as the ecosystem will not be able to support it. Within these areas, there will be higher densities of individuals (e.g. fish or crustaceans). Assuming that the populations are distributed uniformly and that the movement of the individuals is density dependent [36], the individuals will move from high-density areas to other low-density areas— those that are not protected. This migration of the individuals from MPAs to areas that are not protected is known as the spillover effect [25].

Based on the extensions of the models to represent the fishing dynamics in the case of the inclusion of MPAs [2], and considering the plans of the Colombian government to increase the system of MPAs, the purpose of this study is to determine the change in terms of the benefits provided to the society -via fisheries in the scenario whereby the marine protected areas are extended. To do this, a bio-economic model that simulates different conservation scenarios, each characterized by the extension of the MPA, and its respective ecosystems is implemented. The case study presents the results for the white shrimp (*Litopenaeus occidentalis*) fishery in the Colombian Pacific, which is in operation since 1958, through the stages of growth, fully exploited, over exploited and depleted [34]. The model studies the relationship between fishing production and the existence of protected areas, following other similar studies (e.g. [9,7,35]). Three conservation scenarios are defined according to the percentage of marine area under protection. The base scenario considers the current level of protection given by the existing MPA's in Colombia, called here the *status quo*. A second scenario represents the level of protection that would be reached if the marine protected areas were to be increased according to the high-priority areas defined by [23], and defined in Maldonado et al. [26], equivalent to the protection of 4.4% of the marine surface. This scenario is called here the *proposed scenario*. These results are all analyzed against a third scenario that contemplates the possibility of there not being any MPA, named here as the *no-protection scenario*.

The purpose of the model is to test the hypothesis that the implementation of MPAs does not necessarily reduce benefits to fishermen because of the reduction of the area available for fishing; the migration between MPAs and fishing areas will imply that the fishing areas are more productive, despite being smaller, and spillover effect will have a positive impact on the benefits provided for the fisheries. However, fisheries may be victims of the tragedy of commons, exhausting their benefits in the long-term.

These hypotheses are tested through a bio-economic model that simulates the resource dynamics and the benefits obtained in a time horizon of 50 years, comparing the results obtained with the different protection scenarios. The rest of this paper is set out as follows: Section 2 details the methods used to build the bio-economic model; Section 3 presents the main results of the application of the model; and the Section 4 discusses the results and their implications in terms of the country's protection figures.

2. Methods

2.1. Theoretical model

In a marine area, there is a fishing resource whose quantity is expressed in terms of tons of biomass (S). Schaefer's proposal [37] stands out among the models that describe the population growth of a species, whereby this growth, defined as ΔS $(= S_{t+1} - S_t)$, is based on its intrinsic growth rate (r), the size of the population itself (S) and the carrying capacity of the ecosystem (K), following the logistical function, as represented in Eq. (1).

$$\Delta S/\Delta t = S_{t+1} - S_t = rS_t(1 - S_t/K) \tag{1}$$

The model set out in this study represents a marine area divided into two sectors: I) an area under a protection scheme (MPA), where no fishing is allowed, and II) a non-protected marine area, where harvest of resource (white shrimp) is permitted. This means that, in principle, protecting a fraction of the marine area reduces the area available for fishing, and consequently, the amount of resources available for harvesting. Dividing the marine area in two implies that there are also two resource stocks: a population inside the protected area (S_p) and a population in the non-protected area (S_n), and presumably two evolution equations as shown below.

Gordon [18], on the other hand, represents the extraction of the fishing resource (Y), as a function of the fishing effort (E), the size of the population (S) and the species' catchability coefficient (q). White shrimp can only be captured from the fishing area population (S_{n_t}), therefore, the yield or harvest could be defined as:

$$Y_t = qS_{n_t}E_t$$

In this model, E represents the amount of industrial fishing vessels in operation. An extension of this model considers the presence of artisanal fisheries harvesting shrimp in parallel to the industrial fleet. The activity of the artisanal fisheries is assumed not to depend on effort but only on stock abundance, therefore, it is represented as a percentage of biomass, denoted by x. Total effective harvest can be defined as shown in Eq. (2):

$$Y_t = qS_{n_t}E_t + xS_{n_t} \tag{2}$$

Now, the model must consider the fact that stocks from protected area can migrate to fishing areas. For that consideration, the model follows Kar and Matsuda [24]. Following this model, the population inside MPAs is not affected by fishing and therefore it grows more steadily, leading to higher densities of individuals. As a result, individuals might migrate from areas with higher densities to less dense areas, creating the spillover effect [3].

To incorporate this element, Kar and Matsuda [24] represent the spillover effect or migration (M_t) between the MPA and the fishing area depending on the population inside the MPA (S_{p_t}) and in the fishing area (S_{n_t}), the carrying capacity in the MPA (K_{Pt}), and in the fishing area (K_{nt}) and a migration coefficient (z). Eq. (3) describes the spillover