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Marine reserve creation and interactions between fisheries and capture-based aquaculture: A bio-economic model analysis

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Abstract

The rapid growth of aquaculture affects wild fisheries in several ways. We present a bioeconomic model of the interaction between a commercial wild fishery and capture-based aquaculture that depends on harvest of wild juveniles. We assume that aquaculture reduces the intrinsic growth rate of the wild fish stock due to wild caught juveniles used as seeds, influencing wild stock size and commercial harvest. This may increase the economic conflicts between fishers and farmers. Introducing a marine protected area is expected to reduce these conflicts. The model considers both open access and economically optimal management regimes outside the marine protected area using numerical simulation. The numerical results show that a marine protected area of a certain size may increase economic benefits of both fishers and farmers in the case of optimal management, and enhance wild catch outside the reserve when there is open access.

KEYWORDS

aquaculture, bioeconomic model, management, marine protected areas, wild fishery

1 | INTRODUCTION

Total world fish production increased dramatically from 19.3 million tons in 1950 to 148.5 million tons in 2010, with the largest contribution coming from marine capture fisheries (FAO, 2012). However, fish supply from wild fisheries reached a peak and has been fairly stable at about 90 million tons since the late 1980s. Since then, the increase in total fish production has come from aquaculture (Diana, 2009). Aquaculture production reached 59 million tons in 2010, compared to 4.7 million tons in 1980, which is equivalent to an average annual rate of increase of 8.45% (FAO, 2012). As the share of aquaculture contribution in seafood supply increases, the fisheries–aquaculture interactions become important and are receiving ever more attention from researchers (Natale, Hofherr, Fiore, & Virtanen, 2013).

Wild fisheries–aquaculture interactions can be divided into two classes: the market interactions (between wild and farmed fish that are sold as food) and the interactions related to environmental efficiency and wild resource uses (i.e., seed and feed). The former type of interaction may provide positive effects of aquaculture on wild fisheries such as the increase in total supply and reduction in fish price,



resulting in a decline in fishing effort and hence an increase in wild fish stocks and harvest in open access fisheries (Anderson, 1985; Valderrama & Anderson, 2010; Ye & Beddington, 1996). The positive market effects of aquaculture on wild fisheries, however, have only been identified for some species such as sea bream, sea bass, salmon, shrimp, tilapia, and pangasius (Asche, Bjørndal, & Young, 2001; Asche, 2008). For the majority of aquaculture species that are low-intensity, small-scale, and wild seed dependent, productivity-enhancing innovation effects are limited (Asche, 2008). The second type of interaction shows the opposite result; the growth of aquaculture that relies on natural resources has a negative effect on wild fish stocks and hence diminishes wild catch (Hannesson, 2003; Naylor et al., 2000). In addition, the growth of aquaculture creates ecological and environmental impacts such as water and genetic pollution, destruction of coastal environments such as mangrove forests, and results in disease being spread from cultured fish to wild fish (Chopin et al., 2001; Naylor et al., 2000). Though there exist a variety of interactions between wild fisheries and aquaculture, in this study we focus on the external effect of aquaculture requiring juveniles of the same species that is harvested in a wild commercial fishery.

Aquaculture that relies on the collection of live material from the wild is defined as capture-based aquaculture (CBA) (FAO, 2011). A wide range of representative marine and freshwater, vertebrate and invertebrate species are used in CBA practices as seeds and selected from four major groups: mollusks (i.e., mussels, oysters, scallops, cockles), crustaceans (i.e., shrimps, spiny lobsters, crabs), echinoderms (i.e., sea cucumbers), and finfishes (i.e., freshwater eels, milkfishes, air-breathing catfishes, cods, mullets, temperate basses, jacks and pompanos, grouper, snappers, porgies, wrasses, rabbit-fishes, mackerels and tunas, snakeheads) (Sadovy de Mitcheson & Liu, 2008). Though we could find no current CBA coverage data, it was estimated to be at least 20% of the total annual fish aquaculture production in 1997 (Hermansen & Eide, 2013), indicating a substantial industry worldwide. CBA therefore is of concern as it is yet another cause of reduction in juvenile availability with impacts on capture fisheries, and potentially creating economic conflict between users (Sadovy de Mitcheson & Liu, 2008). With the exception of some developed countries where CBA is carried out alongside managed fisheries (i.e., cod in Norway, crab in Australia, yellowtail in Japan), most fisheries around the world, including the wild seed fisheries for CBA, are typically not managed or controlled effectively (FAO, 2011). When wild seed fisheries are poorly managed, growth of CBA may contribute to the threat of overfishing for some species, for example, milkfish in the Philippines; shrimp in Bangladesh; seahorses, humphead wrasse, and grouper in Southeast Asia; European eels; mullet in Egypt; Atlantic Bluefin tuna (FAO, 2011); or even cause fishery collapse, of which the lobster fishery in Vietnam is an example (Thuy & Ngoc, 2004). CBA can be replaced by hatchery-based aquaculture (HBA) in the future, but full conversions to HBA are rare, and CBA can therefore be expected to continue for many species due to biological, social and economic reasons (FAO, 2011). As stated by FAO (2011), such CBA practices require responsible development and management.

Regulations and enforcement of fisheries exploitation face challenges worldwide. Marine protected areas (MPAs) are seen as an alternative fisheries management tool for securing the recovery of overexploited fish stocks and for ensuring sustainable fisheries (Alban et al., 2008). MPAs are usually closed areas for fishing, and as such they therefore not only protect part of the fish stock, but they may also provide protected grounds for spawning, juvenile settlement, nurseries and feeding. Though there are a number of ecological studies showing the recovery of fish stocks both inside and outside MPAs, these effects seem to be largest within the MPA (Halpern, 2003; Halpern, Lester, & Kellner, 2009). The early research on systems consisting of a marine sanctuary and a fishing ground showed that the catch with an MPA might be greater than under solely open access due to migration to fishable areas from a more plentiful stock in the MPA. However, these studies underlined that reserves give less benefits than optimal management (Hannesson, 1998; Holland & Brazee, 1996; Conrad, 1999). Newer research has qualified this aspect, where, for instance, Sanchirico and Wilen (2001) develop a dynamic, spatial



bioeconomic model that suggests both total fish biomass and harvest may under certain circumstances increase after closing and protecting an area from exploitation. Grafton, Kompas, and Van Ha (2009) use northern cod fishery data and counterfactual analysis with stochasticity to show that optimal harvest and an optimal-sized marine reserve could generate more resource rents than optimal harvest without a reserve. MPAs have also been shown to potentially outperform conventional fishery management (i.e., TACs, quotas) by increasing the average intrinsic growth rate of the stock, making it more resilient in the face of large harvest pressure (Punt, Weikard, Groeneveld, Van Ierland, & Stel, 2010; Punt, Weikard, & Van Ierland, 2013; Schnier, 2005a,b).

In this study, we will use a bioeconomic model to analyze the interaction between a commercial adult fishery and aquaculture dependent on wild juveniles, including an MPA effect.¹ Examples of general interactions between aquaculture and wild fisheries are few, but do exist in the literature. For instance, Hoagland, Jin, and Kite-Powell (2003) presented a bioeconomic model in which aquaculture activities reduce the environmental carrying capacity of a wild fish stock, resulting in smaller stock size and harvest from the wild fishery; Mikkelsen (2007) also found that wild fishery production varied dependent upon both aquaculture impacts (i.e., impact on intrinsic growth rate, carrying capacity or catchability) and the choice of management regimes. There is, however, to the best of our knowledge, no study showing the negative effects of CBA on wild adult fisheries while including the introduction of an MPA.²

The presence of CBA can increase natural mortality of the wild fish stock in early life stages, hence reducing the intrinsic growth rate. This, again, reduces the natural growth of the wild stock, impacting the equilibrium wild stock, harvest, and profit. In this vein, Simon et al. (2012) analyzed a dynamic biomass model using all available biological and ecological information regarding Atlantic bluefin tuna to show that the natural mortality of prerecruit stages (larvae and juveniles) and the intrinsic growth rate are indeed strongly and negatively correlated. Similarly, Gedamke, Hoenig, Musick, Dupaul, and Gruber (2007) argue the positive connection between first year survival (albeit without fishing) and the intrinsic growth rate, underlining the connection between juvenile survival and the intrinsic growth rate of fish.

Our study is based on Hoagland et al. (2003), but we assume that CBA reduces the intrinsic growth rate of a specific wild fish stock, rather than the carrying capacity, and expand the bioeconomic model with an MPA. Though many economic studies have questioned the overall benefits of MPAs (Anderson, 2002; Hannesson, 1998), we ask whether MPAs can reduce the economic conflicts between ocean users: fishermen and farmers.

This study makes two main contributions to the literature. The first is an expansion of the Hoagland et al. (2003) model in order to show the effects of the introduction of an MPA on interactions between a wild fishery and CBA. Furthermore, we develop the model to include the impact of CBA on intrinsic growth of the wild stock in a nonlinear functional form.³ This is a novel contribution as to the best of our knowledge, there exists no earlier study of the impact of an MPA on the interaction between aquaculture and wild fisheries. Secondly, we present MPAs as an integrated management tool to reduce potential conflicts between different users of the sea. This is an additional contribution to the scarce but important literature on resolving conflicts between ocean users via zoning, thereby separating conflicting interest groups (Bishop & Samples, 1980; Hoagland et al., 2003; Jin, Kite-Powell, & Hoagland, 2007; Laukkanen, 2001; Lee & Iwasa, 2011). MPAs may however not be conducive for reducing conflict because some fishers may experience an increase in yields from the implementation of MPAs, while others get reductions in harvests (Holland, 2000; Ngoc & Flaaten, 2010; Sumaila, 2002; Sumaila & Armstrong, 2006). Our study shows that introducing an MPA, with optimal harvesting, may not only mitigate the negative external effect of CBA on the wild fishery, but it also increases the economic benefits for both users, contributing to reduce conflicts between resource users.



The remainder of the article is organized as follows. In the next section, we present two CBA–wild fishery interaction models. In the first model, we assume that CBA has an external effect reducing the intrinsic growth rate of the wild fish. In the second model, an MPA is established in a portion of the coastal area, which is protected from fishing and aquaculture, while the remaining portion is left for both users of the ocean. Four management regimes are presented in section three: pure open access, open access in the area outside the MPA, and economic optimum with and without an MPA. Due to the complexity of the interactions, analytical results do not provide any insight, hence numerical simulation is conducted in order to investigate the behavior of the models, and is presented in section four. Section five summarizes the major conclusions and suggests some additional future research.

2 | MODELS

2.1 | Basic fishery model

We start with the original situation where the entire area is open for fisheries. Note that for simplicity all time subscripts of time dependent variables are omitted. Suppose the fish stock obeys the logistic law of growth described by the net growth equation

$$\dot{S} = F(S) - y_f = rS \left(1 - \frac{S}{K}\right) - y_f, \quad (1)$$

With S being the stock size, K is the carrying capacity, r is the intrinsic growth rate, $F(S)$ is the natural growth function, and y_f is the harvest rate. Normalizing stock by dividing stock level with carrying capacity gives the net growth function

$$\dot{X} = F(X) - Y_f = rX(1 - X) - Y_f, \quad X = \frac{S}{K}, \quad Y_f = \frac{y_f}{K}. \quad (2)$$

The net benefit function is described as

$$V(X, Y_f) = \left(Kp_f - \frac{c}{qX}\right) Y_f, \quad (3)$$

where c is a constant unit cost of fishing effort, q denotes catchability, and p_f is constant unit price of fish. All parameters are positive.

2.2 | External effect from CBA on the wild fishery

Now let us introduce CBA that coexists with fisheries in the ocean space. The presence of aquaculture that uses wild juveniles as input is assumed to decrease the intrinsic growth rate of the wild fish stock. In our model we also assume that aquaculture does not affect the distribution of fish. This assumption is reasonable if aquaculture activities are allocated in a minor part of the total ocean area, and operate in a section of limited importance to the wild fish stock (Mikkelsen, 2007).

Let N be produced volume of farmed fish, and the intrinsic growth rate of wild fish can be now redefined as⁴

$$\tilde{r} = \tilde{r}(N) = r \left(1 - \exp\left(-\frac{1}{\alpha N}\right)\right), \quad \tilde{r} > 0 \text{ for all } 0 < N < \infty, \quad (4)$$

where $\alpha > 0$ is the aquaculture sensitivity coefficient influencing the intrinsic growth rate of wild fish. The expression implies that the intrinsic growth rate of wild fish declines with an increase in aquaculture production in a nonlinear way, with $\tilde{r} = \tilde{r}(0) = r$ and $\tilde{r} = \tilde{r}(\infty) = 0$. Incorporation of a CBA external



effect into the intrinsic growth rate of wild fish results in a change in the natural growth function to $F(X, N)$. Particularly, more CBA production means lower natural growth of wild fish, that is, $\frac{\partial F(X, N)}{\partial N} = F_N(X, N) < 0$ and $\frac{\partial^2 F(X, N)}{\partial N^2} = F_{NN}(X, N) \geq 0$.

The net growth equation will now be

$$\dot{X} = F(X, N) - Y_f = \tilde{r}(N)X(1 - X) - Y_f. \quad (5)$$

The economic dimensions of the aquaculture operation will be characterized following Hoagland et al. (2003) with adjustments involving different prices for aquaculture and wild fish, nonlinear cost of aquaculture and a nonlinear effect of aquaculture on wild fish intrinsic growth. The aquaculture operating cost (e.g., feed, seed, labor, boats, interest, and other capital items), $C_a(N)$, is a nonlinear and increasing function of total aquaculture production: $C_a(N) = \nu N^2$, with $\frac{\partial C_a}{\partial N} > 0$ and $\frac{\partial^2 C_a}{\partial N^2} \geq 0$. The investment cost in new aquaculture facilities (e.g., the components and devices of aquaculture), $I(z)$, is a linear function of the increment, z , to the total aquaculture production: $I(z) = bz$.⁵ Parameters ν and b are positive and constant, denoting the unit operating cost of aquaculture and the cost of investment in new aquaculture facilities for a unit of produced volume of farmed fish, respectively.

For simplicity of exposition while at the same time allowing focus on trade-offs, we assume the market price of fish, p_i ($i = f$ denotes price of wild fish and $i = a$ price of cultured fish), are constant, and the price for wild fish is higher compared to farmed fish. A constant fish price may be a strong assumption as the contribution of aquaculture production to the total fish production may result in lower fish prices for several species as shown by Asche et al. (2001) and Asche (2008). However, for most CBA which is low-intensity and small-scale, the scope for development in the farming process resulting in aquaculture production increase is limited (Asche, 2008). Hence, the local production provided by CBA species is small compared to total worldwide production. For example, the 2013 size of CBA of Atlantic cod in Norway, yellowfin tuna in Japan, and lobster in Vietnam was a relatively insignificant share of about 0.3%, 0.01%, and 0.4%, respectively, of the total worldwide production.⁶ We therefore assume that there is no aggregate quantity effect associated with such CBA industries on the global fish price, and set price as an exogenous variable taking a constant value. The total net benefit is defined as the sum of net benefits from the wild fishery and aquaculture taking the form:

$$V(X, N) = \left(Kp_f - \frac{c}{qX} \right) Y_f + [p_a N - C_a(N) - I(z)]. \quad (6)$$

2.3 | MPA creation

Now let us implement an MPA in the system: subarea 1 includes both the wild fishery and aquaculture, and subarea 2 is an MPA where fishing and aquaculture are forbidden. The total normalized population, hence, consists of two normalized subpopulations, X_1 and X_2 , which have the same homogeneous characteristics and $X = X_1 + X_2 = \frac{S_1}{K} + \frac{S_2}{K}$. The total distribution area is set equal to one with subareas 1 and 2 equaling $(1 - m)$ and m , respectively, $0 < m < 1$. Each subpopulation has an individual carrying capacity which is proportional to the size of the subarea. The creation of an MPA raises the possibility of migration or diffusion if there is a difference between the densities of the subpopulation, that is, $\frac{X_1}{1-m}$ and $\frac{X_2}{m}$. We assume that there is net migration from the MPA, where there is higher population density compared to the fishing ground, and the two subpopulations are distributed homogeneously throughout their respective subareas. Therefore, net emigration from the MPA equals net immigration to the fishing ground at a rate $M(X_1, X_2) = \gamma \left(\frac{X_2}{m} - \frac{X_1}{1-m} \right)$, where $\gamma > 0$ is the migration coefficient.⁷

To simplify, we assume that $r_1 = r_2 = r$ in the case without an external effect of CBA. The intrinsic growth rate of the fish stock in the fishable area follows (4) when there are externalities of CBA



on wild fisheries. This implies that the presence of CBA reduces the intrinsic growth rate of the fish stock in the fishing ground, with the natural growth rate $F_1(X_1, N)$, implying $\partial F_1(X_1, N)/\partial N = F_{1N}(X_1, N) < 0$.

The subpopulation net growths in the two areas are

$$\begin{aligned} \dot{X}_1 = F_1(X_1, N) + M(X_1, X_2) - Y_{1f} &= r \left(1 - \exp\left(-\frac{1}{\alpha N}\right) \right) X_1 \left(1 - \frac{X_1}{(1-m)} \right) \\ &+ \gamma \left(\frac{X_2}{m} - \frac{X_1}{(1-m)} \right) - Y_{1f}, \end{aligned} \quad (7)$$

$$\dot{X}_2 = F_2(X_2) - M(X_1, X_2) = rX_2 \left(1 - \frac{X_2}{m} \right) - \gamma \left(\frac{X_2}{m} - \frac{X_1}{(1-m)} \right), \quad (8)$$

where, Y_{1f} is the normalized harvest in subarea 1, assumed to be proportional to the population density on the fishing ground. This implies the adjusted Schaefer harvest function $Y_{1f} = \frac{qEX_1}{(1-m)}$ (Flaaten & Mjølhus, 2005, 2010).

The total net benefit from the wild fishery and CBA takes the form

$$V(X_1, N) = \left(Kp_f - \frac{c(1-m)}{qX_1} \right) Y_{1f} + [p_a N - C_a(N) - I(z)]. \quad (9)$$

3 | MANAGEMENT REGIMES

3.1 | An open access regime

3.1.1 | External effect from CBA on the wild fishery

The external effect from CBA on the wild fishery depends on produced volume of farmed fish, N . We assume that CBA is a competitive industry in the open access fishery case. In open access equilibrium, the steady-state normalized wild stock is $X^\infty = \frac{S^\infty}{K} = \frac{c}{Kqp_f}$ and the steady-state normalized harvest rate is derived from equation (5) giving $Y_f^\infty = F(X^\infty, N) = r(1 - \exp(-\frac{1}{\alpha N}))X^\infty(1 - X^\infty)$.⁸ The steady-state equilibrium wild stock does not depend on CBA production while the steady-state equilibrium wild catch does. The wild catch declines when the CBA production increases.

3.1.2 | MPA creation

When we introduce an MPA in the system, the grounds available for fishing and CBA become smaller than without an MPA. The assumption of the distribution of fish being unaffected by marine farming is kept. In equilibrium, the steady-state normalized stock in the MPA can be calculated as

$$X_2 = -\frac{1}{2} \left(\frac{\gamma}{r} - m \right) + \sqrt{\frac{1}{4} \left(\frac{\gamma}{r} - m \right)^2 + \frac{\gamma m X_1}{r(1-m)}}. \quad (10)$$

For open access in subarea 1, the steady-state normalized stock is $X_1^\infty = X^\infty(1-m) = \frac{c}{Kqp_f}(1-m)$. Substituting X_1 with this in equation (10), we can find X_2 . The steady-state wild stock size in the entire area will be $S = S_1^\infty + S_2 = KX_1^\infty + KX_2$. From equations (7) and (8),



we can find the steady-state harvest rate $Y_{1f}^\infty = F_1(X_1^\infty, N) + F_2(X_2)$. The catch in tons is $y_{1f}^\infty = (1 - m) K[F_1(X_1^\infty, N) + F_2(X_2)]$.

3.2 | An optimal management regime

3.2.1 | External effect from CBA on the wild fishery

A manager chooses the level of harvest, Y_f , and the level of investment in CBA, z , in order to maximize the net present value (NPV) of fish production from both CBA and the wild fishery:⁹

$$\max_{Y_f, z} \int_0^\infty \left\{ \left[\left(K p_f - \frac{c}{qX} \right) Y_f \right] + [p_a N - C_a(N) - I(z)] \right\} e^{-\delta t} dt \tag{11}$$

subject to

$$\dot{X} = F(X, N) - Y_f, \quad X(0) = X_o, \quad X(t) \geq 0, \quad 0 \leq Y_f \leq Y_{fmax}, \tag{12}$$

$$\dot{N} = z, \quad N(0) = 0, \quad N(t) \geq 0, \quad z \geq 0. \tag{13}$$

The current-value Hamiltonian for this problem may be described as

$$H^c = \left[\left(K p_f - \frac{c}{qX} \right) Y_f \right] + [p_a N - C_a(N) - I(z)] + \lambda [F(X, N) - Y_f] + \beta z. \tag{14}$$

With λ and β being the adjoint variables measuring the shadow prices of the associated state variables X and N , the first-order conditions for an optimal solution include

$$\lambda = \left(K p_f - \frac{c}{qX} \right), \tag{15}$$

$$\beta = b, \tag{16}$$

$$\dot{\lambda} = \delta \lambda - \frac{c Y_f}{q X^2} - \lambda F_X(X, N), \tag{17}$$

$$\dot{\beta} = \delta \beta - p_a + 2vN + \lambda F_N(X, N). \tag{18}$$

The current-value Hamiltonian is linear in the controls, strictly concave in the state variable X , while the growth function $F(X, N)$ is convex in N . This implies that the need to check for the signs of the second derivative of H^c for the current-value Hamiltonian to be concave in X and N , giving the problem a unique solution.¹⁰ The same expression is the case for the optimal management with an MPA.

If the signs of the second derivative of H^c hold, the current-value Hamiltonian is concave, and equations (15)–(18), together with equation (12) can be used to solve for optimal solutions of X^* , N^* , Y_f^* , and the two shadow prices. Equation (16) shows that β , the shadow price of N , is constant and positive, being a traditional “bang–bang” equilibrium, suggesting aquaculture investment should be made as quickly as possible to optimize the size of aquaculture (N^*). The NPV of the wild fishery and CBA at bioeconomic optimum becomes

$$V(X^*, N^*) = \frac{\left[\left(K p_f - \frac{c}{qX^*} \right) F(X^*, N^*) + \left(p_a N^* - v(N^*)^2 \right) \right]}{\delta} - bN^*. \tag{19}$$



3.2.2 | MPA creation

When the original ground is divided into two subareas, one is set aside as an MPA and the other is used for fisheries and aquaculture. We consider the problem where a manager seeks to maximize the net profits from both fishery and aquaculture by choosing the levels of wild harvest, Y_{1f} , and aquaculture investment, z .

$$\max_{Y_{1f}, z} \int_0^{\infty} \left\{ \left(K p_f - \frac{c(1-m)}{qX_1} \right) Y_{1f} + [p_a N - C_a(N) - I(z)] \right\} e^{-\delta t} dt \quad (20)$$

subject to

$$\dot{X}_1 = F_1(X_1, N) + M(X_1, X_2) - Y_{1f}, \quad X_1(0) = X_{01}, \quad X_1(t) \geq 0, \quad 0 \leq Y_{1f} \leq Y_{1fmax}, \quad (21)$$

$$\dot{X}_2 = F_2(X_2) - M(X_1, X_2), \quad X_2(0) = X_{02}, \quad X_2(t) \geq 0, \quad (22)$$

$$\dot{N} = z, \quad N(0) = 0, \quad N(t) \geq 0, \quad z(t) \geq 0. \quad (23)$$

The current-value Hamiltonian for this problem may be expressed as follows:

$$\begin{aligned} H^c = & \left(K p_f - \frac{c(1-m)}{qX_1} \right) Y_{1f} + [p_a N - C_a(N) - I(z)] + \lambda_1 [F_1(X_1, N) + M(X_1, X_2) - Y_{1f}] \\ & + \lambda_2 [F_2(X_2) - M(X_1, X_2)] + \beta z. \end{aligned} \quad (24)$$

With λ_1 , λ_2 , and β being the adjoint variables measuring the shadow prices of the associated state variables X_1 , X_2 , and N , the first-order conditions for an optimal solution become

$$\lambda_1 = \left(K p_f - \frac{c(1-m)}{qX_1} \right), \quad (25)$$

$$\beta = b, \quad (26)$$

$$\dot{\lambda}_1 = \lambda_1 \left(\delta - F_{1X_1}(X_1, N) + \frac{\gamma}{1-m} \right) - \frac{c(1-m)Y_{1f}}{qX_1^2} - \frac{\lambda_2 \gamma}{1-m}, \quad (27)$$

$$\dot{\lambda}_2 = \lambda_2 \left(\delta - r \left(1 - \frac{2X_2}{m} \right) + \frac{\gamma}{m} \right) - \frac{\lambda_1 \gamma}{m}, \quad (28)$$

$$\dot{\beta} = \delta \beta - p_a + 2vN + \lambda_1 F_{1N}(X_1, N) \quad (29)$$

This is similar to the case of the CBA–fisheries interaction, as equation (26) suggests that aquaculture investment should be made as quickly as possible in order to reach the optimal aquaculture size (N^*). Assuming that a steady-state equilibrium is feasible (i.e., the current-value Hamiltonian is a concave function), equations (25)–(29), together with equations (21) and (22) can be used to solve for



optimal solutions of X_1^* , X_2^* , N^* , and Y_{1f}^* and three shadow prices. The NPV of the wild fishery and aquaculture at bioeconomic optimum becomes

$$V(X_1^*, N^*) = \frac{\left[\left(K p_f - \frac{c(1-m)}{q X_1^*} \right) [F_1(X_1^*, N^*) + F_2(X_2^*)] + (p_a N^* - v(N^*)^2) \right]}{\delta} - b N^*. \tag{30}$$

The analytical solutions of the optimal management models with and without an MPA involve multiple roots, are cumbersome, and give no further insight. Hence, we apply a numerical procedure in order to find optimal solutions and to test whether equilibrium states are robust with respect to changes in parameter values.

4 | NUMERICAL SIMULATIONS

In this part, we set values for the parameters $r, K, p_f, p_a, q, c, \alpha, \gamma, v, b, \delta$ (see Table 1) and numerically solve for the cases of open access and optimal management in equilibrium.¹¹

4.1 | Open access regime

As can be seen in equations (3) and (5), the equilibrium wild stock level is independent of the presence of CBA, while the equilibrium wild catch is affected by CBA operations. Given the parameter values and a level of CBA production (here we assume $N = 1221 \times 10^{-3}$, which is the optimal size of CBA in the case without an MPA effect), we observe that the total stock size is greater when an MPA is introduced and increases with increasing MPA size (see Figure 1), while the wild catch varies with increasing MPA size. The impact of MPA creation on harvests, as shown in Figure 2, yields a higher wild catch compared to pure open access, except for a relatively large MPA (at least 80% of the entire area).

4.2 | Optimal management regime

We use the software package Mathematica to determine the optimal output variables for a given reserve size. Given the parameter values and model specification, the economic optimal values of normalized

TABLE 1 Parameters for wild fishery and CBA

Variable	Description	Value
α	CBA sensitivity coefficient	3
v	CBA production operating cost	0.4
c	Unit cost of fishing effort	0.3
q	Catchability coefficient	1
p_f	Unit price of wild fish	1.2
p_a	Unit price of farmed fish	1
r	Intrinsic growth rate	0.4
b	Investment cost	0.2
γ	Migration coefficient	0.5
δ	Discount rate	0.07
K	Carrying capacity	1

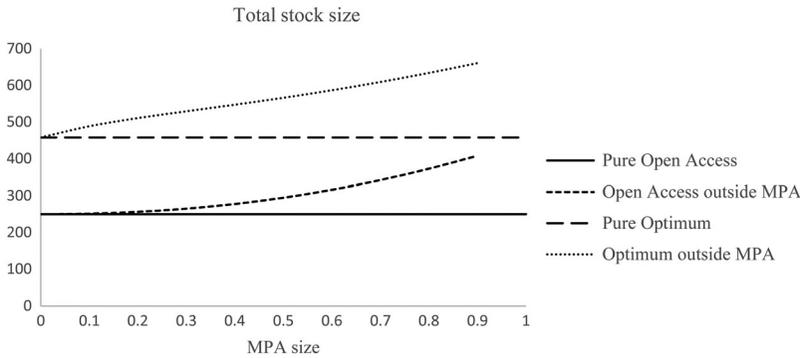


FIGURE 1 Effect of varying size of MPA (m) on wild fish stock size under both open access and optimal management regimes (values in 10^{-3})

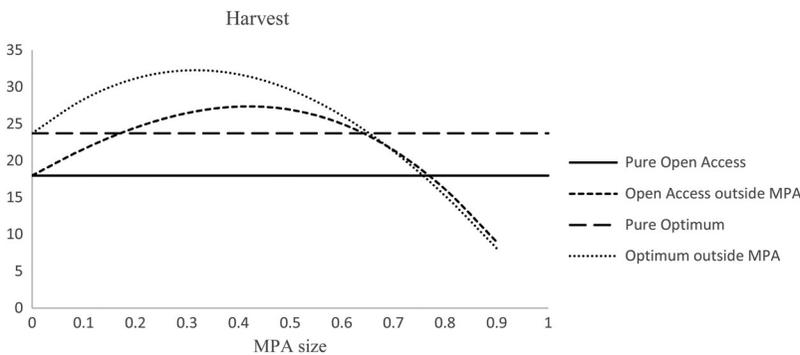


FIGURE 2 Effect of varying size of MPA (m) on wild harvest under both open access (given the optimal level of CBA production: $N = 1221$) and optimal management regimes (values in 10^{-3})

TABLE 2 Simulation results varying m for steady-state equilibria in bioeconomic optimum, and comparing to without an MPA (all values in 10^{-3})

Output variable	Description	Without MPA	With MPA (m)					
			0.1	0.15	0.2	0.3	0.4	0.5
			438	422	402	358	310	260
S_2^*	Stock size in MPA		51	79	109	171	238	307
S^*	Total stock size	458	489	501	511	530	548	566
N^*	Amount of aquaculture activity	1221	1221	1222	1222	1223	1225	1226
y_f^*, y_{1f}^*	Harvest in tons	24	28	30	31	32	32	30
V^*	Total NPV	8864	8888	8889	8882	8847	8785	8699
V_f^*	NPV from wild fishery	185	208	209	202	167	105	19
V_N^*	NPV from aquaculture	8680	8680	8680	8680	8680	8680	8680

wild fish stock and harvest, aquaculture production level, total net profits and profit for each user in the case with and without an MPA are calculated.¹² We can then estimate stock sizes and harvest rate in volume as in Table 2.¹³ Testing for stability of the steady-state equilibrium solutions shows that they are locally asymptotically stable.

The results from the numerical simulation show that the wild fishery (i.e., total stock size and wild harvest) exhibits the same tendencies as that of open access. The optimal stock size increases with an



increasing MPA size and is larger than without an MPA, while the optimal wild catch with an MPA varies depending on the MPA size. The optimal wild catch is higher than without an MPA, except for an MPA size greater than 65% of the entire area (see Figure 2). Because the optimal wild catch increases with an increase in MPA size up to about 0.35 and then decreases for a larger MPA size, the wild fishery NPV and total NPV with an MPA show the same general tendencies as that of wild catch. The total NPV can be maximized for a certain MPA size (i.e., $m = 0.15$ in this simulation). The CBA production (i.e., produced volume and NPV) increases slightly for an increasing MPA size and is larger than without an MPA.

For an MPA larger than 55% of the entire area, the wild fishery NPV is negative. This is due to the fact that despite a larger MPA increasing spillover to the fishery, it also reduces the share of the population that becomes available for harvest (Grafton, Kompas, & Lindenmayer, 2005). When increasing MPA size such that $m > 0.55$, the gain from the increase in spillover as a result of the larger biomass, is smaller than the cost of the loss in harvest from the area prior to reserve creation. Hence, there would be no incentive to expand the MPA any further. In this simulation, it should be noted that an MPA is beneficial to fishers (i.e., fishery NPV for a certain size of MPA is greater than without an MPA) only if the negative impact of CBA on the intrinsic growth rate of wild fish stock is large enough (e.g., presence of CBA reduces the intrinsic growth rate of wild fish stock by at least 65%, or the CBA sensitivity coefficient α must be greater than 2).

These numerical simulation results are an illustration of the model, and are a function of the chosen parameters. We therefore study the effect of minor changes (10% increase) for each parameter value on the optimal solutions for situations both without an MPA ($X^*, Y_f^*, N^*, V^*, V_f^*, V_N^*$) and with an MPA ($X_1^*, X_2^*, Y_{1f}^*, N^*, V^*, V_f^*, V_N^*$). The model exposes different sensitivity to change in the parameter values. To enable comparison of this sensitivity, these changes are presented as elasticities, or the ratio of percentage change in the values of output variables to percentage change in the parameter values in the neighborhood of the initial values. This is presented in Table 3.

Table 3 shows that the optimal values in both cases with and without an MPA are robust with regards to the chosen parameter values, except for the intrinsic growth rate, r , price of wild and farmed fish, p_f and p_a , CBA operating costs, v , and CBA sensitivity coefficient, α , each of which suggests that a 10% change in parameter causes more than a 10% change in optimal value. Interestingly, the introduction of an MPA increases the robustness of the model, that is, the elasticities of optimal variables decline when an MPA effect is included in the model. Furthermore, when introducing an MPA the model becomes robust to the perhaps most uncertain parameter, the CBA sensitivity coefficient α .

TABLE 3 Sensitivity analysis

10% increase in parameter	% change in optimal value												
	Without an MPA						With an MPA ($m = 0.1$)						
	X^*	Y_f^*	N^*	V^*	V_f^*	V_N^*	X_1^*	X_2^*	Y_{1f}^*	N^*	V^*	V_f^*	V_N^*
α	-2.2	-10.1	0.1	-0.2	-13.0	0.0	-1.4	-1.3	-6.5	0.1	-0.2	-8.0	0.0
v	2.3	9.2	-11.2	-10.4	11.6	-11.0	1.4	1.3	6.2	-11.2	-10.4	7.5	-11.0
c	5.1	0.5	0.1	-0.1	-6.3	0.0	4.4	4.3	-0.1	0.1	-0.2	-7.0	0.0
q	-5.2	-0.9	-0.1	0.1	5.1	-0.0	-4.5	-4.3	-0.2	-0.1	0.2	5.7	-0.0
p_f	-5.2	-0.8	-0.2	0.4	14.7	-0.0	-4.5	-4.3	-0.2	-0.2	0.5	15.2	-0.0
p_a	-2.5	-10.4	10.4	18.8	-13.8	19.3	-1.4	-1.4	-6.7	10.4	18.7	-8.3	19.3
r	2.6	10.4	-0.1	0.3	13.2	-0.0	2.1	2.4	10.1	-0.1	0.4	12.1	-0.0
b	0.0	0.1	-0.2	-0.3	0.2	-0.3	0.0	0.0	0.1	-0.2	-0.3	0.1	-0.3
γ							0.0	-0.4	0.0	0.0	0.0	0.1	0.0

Note: Numbers in bold show sensitive results.



There is a change in the signs of the elasticities of harvest with regard to the cost of effort, c , from positive to negative in the case without and with an MPA, respectively. An increase in this parameter leads to an increase in harvest in the case without an MPA, because when c increases the total fishing cost increases, resulting in a decrease in fishing effort, E , at maximum economic yield (MEY), and hence an increase in the stock size, X , at MEY. If the absolute value of a decline in E at MEY is smaller than the value of an increase in X at MEY, then an increase in c results in an increase in harvest, Y_f . Introducing an MPA may induce a stronger effect of c on the decline of E compared to the effect on the increase in X_1 at MEY, resulting in a decline in harvest, Y_{1f} . The negative sign of the harvest elasticities for a change in price of wild fish, can be explained in a similar way.

5 | DISCUSSION AND CONCLUSION

Competition between ocean user groups is getting increased attention from scientists (Bishop & Samples, 1980; Hoagland et al., 2003; Jin et al., 2007; Laukkanen, 2001; Lee & Iwasa, 2011). Fishermen and marine farmers are competitive ocean users when aquaculture uses seeds (i.e., juveniles) extracted from the wild, causing an increase in fishing mortality of the wild stock, resulting in the reduction of commercial wild fisheries targeting adult individuals. In this study, we develop a model to analyze the interaction between CBA and wild adult fisheries assuming that the impact of CBA on wild fisheries is via reduction of the intrinsic growth rate of the wild fish stock and hence wild stock and harvest. An MPA can be considered a potential management tool to ensure that sufficient numbers of young fish reproduce for the persistence of the population. We therefore include an MPA effect in this interaction model to test whether or not an MPA can enhance economic benefits of both fishers and farmers. The model is applied for both open access and economically optimal management regimes.

As indicated by the sensitivity analysis, the results, with and without an MPA, are most sensitive to change in price of wild and farmed fish, operating costs of CBA, and the intrinsic growth rate of wild fish. While the last term is a biological parameter, the three first parameters, however, can relatively easily be identified in the market.

Given the assumption of the negative effect of CBA on the intrinsic growth rate of wild fish, our model results in a decline in the wild fish growth rate and hence wild harvest. Implementing an MPA of a certain size may reduce the conflicts of interests between fishers and farmers. Under open access, the steady-state equilibrium wild stock level is independent of the presence of CBA, it increases with increasing MPA size and is larger than without an MPA.¹⁴ The wild catch, however, is negatively affected by CBA production and varies depending on the MPA size. With a certain size of MPA, it is greater than pure open access. This result is somewhat similar to existing studies (Hannesson, 1998; Sanchirico & Wilen, 2001), despite our underlying model including a CBA effect on wild fisheries outside the reserve.

However, in the literature a closed area combined with an optimal management policy is not considered to be as beneficial as pure optimal fisheries management policies in a deterministic model, as aggregate biomass can be increased, but fishing yield decreases for increasing marine reserve sizes (Anderson, 2002; Conrad, 1999). Contrary to this, our results show that the implementation of MPAs of certain sizes combined with optimal management outside the reserve can give better results (e.g., wild catch, CBA production, NPVs) in comparison to optimal management without an MPA. These results are mainly driven by the assumption that CBA reduces the intrinsic growth rate of the fish stock in the fishing ground, resulting in a higher intrinsic growth rate within the MPA compared to the fishable area. The migration of fish into the fishable area will increase due to the higher natural reproductive rate within the MPA, allowing for higher values for both fishery and aquaculture compared to optimal management without an MPA.



Our result is somewhat in agreement with Punt et al. (2010, 2013) and Schnier (2005a,b) who suggest that establishing an MPA can benefit a fishery if the resource has heterogeneous growth. Their models require that an MPA increases the average intrinsic growth rate in the unfished area, while our model places the growth moderation on the other side: CBA reduces the intrinsic growth rate of fish in the fished area. However, our study does not only indicate the positive impacts of MPAs on wild fisheries by definition, it also points to another important impact of MPAs, namely that they may mitigate economic conflicts between ocean resource users.

Our findings are of interest because they show that an MPA of a certain size combined with economically optimal harvest and CBA investment can increase the economic benefits for both users. It should however be noted that there are various issues that need to be considered when using MPAs as a management tool for sustainable fisheries and CBA. For instance, the knowledge of the biology of the target species (i.e., spawning sites and times, critical habitats for juveniles, migration routes) is essential in planning MPAs in order to sustainably manage wild populations and continue to supply economic and societal benefits. We, however, simplify the issues for the MPA implementation in order to discuss the use of MPAs as a management tool for solving conflicts between diverse ocean resource users.

MPAs are a well-known, if also criticized, tool for fishery management and may provide a useful approach to avoid and solve conflicts between ocean users, such as fishers and farmers. However, MPAs also provide other potential benefits such as tourism, research, and educational activities. In future work, considering these activities together with the benefits from fisheries and aquaculture should allow the definition of a broader social value of MPAs.

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¹ In this study, the term MPAs are defined as the no-take zones.

² Our model is similar to models presented by Schnier (2005a,b) and Punt et al. (2010, 2013) as they present MPAs that increase the intrinsic growth rate of fish stock. Our model works in the opposite direction: the CBA reduces the intrinsic growth rate of fish stock outside the MPA. We do not, however, only consider the CBA operation as the environmental effect upon the commercial fisheries, but we also include economic conflicts between ocean resource users.

³ Mikkelsen (2007) modeled a linear external effect of aquaculture on the growth rate of the fish stock.

⁴ Simon et al. (2012) indicate that the relationship between the intrinsic growth rate and the natural mortality of the fish stock in early life stages can be described by a decreasing convex relationship. In this article, we assume that CBA development increases the natural mortality of the wild fish stock in early life stages, thus the functional form of the intrinsic growth rate is described as in equation (4).

⁵ For simplicity, we assume the investment costs of CBA take a linear functional form so that the optimization problem is linear in the control variable, z , the level of investment in CBA.

⁶ The estimates of CBA and worldwide production are based on the Food and Agricultural Organization's (FAOs) FishStat database.

⁷ The MPA model of this article is based on the basic MPA model suggested by Conrad (1999) and Hannesson (1998), and presented as Model B in Flaaten and Mjølhus (2010).

⁸ The net profit of the fishery is $\pi(S, y_f) = (p_f - \frac{c}{qS})y_f$, where y_f is harvest rate in tons. In open access the net profit becomes zero, and the stock size will be $S^\infty = \frac{c}{qp_f}$, while the normalized stock is $X^\infty = \frac{S^\infty}{K} = \frac{c}{Kqp_f}$.

⁹ Note that the fish stock ($S(t)$, $X(t)$, $X_1(t)$, $X_2(t)$), harvest ($y_f(t)$, $Y_f(t)$, $Y_{1f}(t)$), aquaculture acreage $N(t)$, aquaculture investment $z(t)$, adjoint variables $\lambda(t)$ and $\beta(t)$ are all time dependent variables.

¹⁰ H^c is concave in X and $N \Leftrightarrow H_{XX}^c \leq 0$, $H_{NN}^c \leq 0$, and $H_{XX}^c \cdot H_{NN}^c - H_{XN}^{c2} \geq 0$.

¹¹ The purpose of this study is to examine whether MPA creation can alleviate the conflicts of interests between wild fisheries and CBA. We therefore consider a case where under economic optimality, both users coexist, and ignore two other potential optimal outcomes (corner

solutions) resulting in only one of the two uses. Given our baseline parameter values, the model produces an internal stable steady-state equilibrium. However, the corner solutions may result if there are significant changes in any parameter or parameter combination.

¹² Given the parameter values, the resulting values of the optimal solutions for fish stock, harvest, and aquaculture production are inserted into the second derivative of the current-value Hamiltonian function, H^c , subject to X and N . The results show that the signs of the second derivative of H^c satisfy the demands for a concave current-value Hamiltonian function, implying the problem has a unique solution.

¹³ The stock sizes, S_1^* , S_2^* , S^* , and catch in weight, y_f^* , y_{1f}^* , can be calculated as follows:

$$S_1^* = KX_1^*; \quad S_2^* = KX_2^*; \quad S^* = S_1^* + S_2^*; \quad y_f^* = KY_f^* = KF(X^*, N^*);$$

$$y_{1f}^* = (1 - m)KY_{1f}^* = (1 - m)K[F_1(X_1^*, N^*) + F_2(X_2^*)].$$

¹⁴ The fact that CBA in our analysis does not affect the equilibrium stock under open access is basically a consequence of applying the Gordon–Schaefer model combined with the assumption that CBA reduces the intrinsic growth rate of the fish stock. Applying a cohort model, or a two-stock model, with a mature and an immature substock could have allowed the CBA to impact the equilibrium stock in the fishery. However, in principle a two-stock model with stock interactions may have similar characteristics to that of a one-stock model with an effect via the intrinsic growth rate.

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