Planning marine protected areas: a multiple use game

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Abstract:

The EU Marine Strategy Directive has a regional focus in its implementation. The Directive obliges countries to take multiple uses and the marine strategies of neighboring countries into account when formulating marine strategies and when designating marine protected area (MPA's). We use game theoretical analysis both to find the optimal size of marine protected areas with multiple uses by multiple countries, and to investigate the influences of multiple use on cooperation. To this end we develop a model in which two specific uses, fisheries and nature conservation, by multiple countries are considered in a strategic framework.

The results of the paper suggest that EU marine policy such as the Marine Strategy Directive and the coming Maritime Policy may help to secure the highest possible benefits from these MPAs if these policies induce cooperation among countries, but only if the policies force the countries to consider all possible uses of marine protected areas. In fact cooperation on a single issue may give a worse outcome than the non-cooperative equilibrium. The results also indicates that cooperation may be hard to achieve because of defector incentives, and therefore if the current policy measures should be strict in enforcing cooperation on all possible uses of MPAs.

Keywords: Marine protected areas, Marine reserves, Bioeconomic model, Game theory, Fisheries, Species richness, Species-area curves, Multiple use

1 Introduction

The marine environment supplies several goods and ecosystem services to society. Yet it is also under increasing pressure from a variety of human activities, such as fisheries, oil & gas exploration and shipping. To extract the goods and services sustainably and to protect vulnerable ecosystems we need to manage human activities in the marine domain.

The European Commission is at the forefront in safeguarding and exploiting its Exclusive Economic Zones (EEZs). This is reflected in its policies and new initiatives such as the Common Fisheries Policy (EU [2009a]), the Water Framework Directive (EU [2009b]), the Maritime Policy (European Commission [2006]) and the Marine Strategy Directive (MSD) (European Commission [2007]). All of these call for ecosystem management, a holistic view and planning at a regional sea level, i.e. between countries sharing a common sea, such as the North Sea. The EU MSD explicitly calls for the formulation of integrated marine strategies by its member states, which should "apply an ecosystem-based approach to the management of human activities while enabling the sustainable use of marine goods and services" (European Commission [2007] article 1.1 and 1.2). Consequently we need to consider regional seas as single entities, surpassing the boundaries of individual countries.

The necessary integration of the management plans both within countries as well as between countries, is far from being reached. The management plans for the individual member states' Exclusive Economic Zones (EEZs) are not always in concordance with each other (Stel [2003], Douvere et al. [2007]) and planning and policymaking at the national level is often fragmented since responsibilities for different activities are divided between different organizations, institutions and ministries (Stel [2002]). The fragmentation favors an attitude in which the effects of human activities are considered in isolation, whereas the effects are actually interdependent and cumulative (Elliott [2002], ICES [2003], de la Mare [2005]).

To manage our seas sustainably we need to develop tools and policy instruments that are capable of achieving goals that have been set at the EU level, and mitigate the fragmentation at lower levels. Marine Protected Areas (MPAs) may be such a tool. They have been proposed for fisheries management for a long time (Guénette et al. [1998]) and more recently also as a tool to tackle biodiversity conservation, ecosystem restoration, regulation of tourist activities and as an example of integrated coastal management if all of these are included (Jones [2002]).

MPAs have limitations, due to their inherent static and delineated nature versus the open and dynamic nature of the marine environment (Allison et al. [1998]). Economists are often skeptical about the effects of marine reserves as fisheries management tools (e.g. Hannesson [1998], Anderson [2002]). The main reasons for designating MPA's that has been advocated by economists are uncertainties and shocks (e.g. Lauck et al. [1998], Sumaila [2002]). Many such analyses, however, focus on fishing effects on a single stock under open access, and exclude the other effects of marine reserves such as biodiversity conservation. Moreover fishing has a destructive effect on habitats (Jennings and Kaiser [1998], Jennings et al. [2001], Auster et al. [1996], Armstrong and Falk-Petersen [2008]) and hence areas that are protected and where no fishing occurs may have a positive effect on the growth rate of the fish stock outside the reserve through habitat enhancement and the preservation of the nursery function of the reserve (Armstrong [2007], Armstrong and Falk-Petersen [2008], Schnier [2005a], Rodwell et al. [2002]).

The multiple uses of MPAs and their impacts on the marine ecosystem require full cooperation among all countries that share a regional sea such as the North Sea. On the one hand, strategic interaction and sub-optimal policy outcomes may occur because in general no central authority exists that can enforce cooperation on these issues. On the other hand, if the various functions of marine protected areas (e.g. in terms of fisheries and nature conservation) are linked, the advantages of cooperation may increase in such a way that self-enforcing agreements can be formed.

In this paper we will analyze the problem of multiple use MPAs by multiple countries using game theory. This provides insights into the functioning of marine protected areas as a policy instrument for the MSD and the Maritime Policy Directive. More specifically, we will examine the size of MPAs that countries assign, when these countries account for the effects of MPAs on fisheries and species conservation separately or jointly and investigate the effect of playing cooperatively versus Nash equilibrium on a single issue when multiple issues are at stake.

Game theory has considered the strategic interaction between countries in a general fisheries context (see e.g. Munro [1979], Levhari and Mirman [1980], Hämäläinen et al. [1985], Vislie [1987], Hannesson [1997], Arnason et al. [2000], Bjørndal and Lindroos [2004], Kronbak and Lindroos [2007]). The related problems of public good provision, international environmental agreements and enforcement has also been considered both in terms of transboundary pollution abatement and coalitions (see e.g. Mäler [1989], Mäler and De Zeeuw [1998], Finus [2003], Weikard et al. [2006], Finus [2006] and Nagashima, et al. [2009]) and in terms of possible coalitions for fisheries management (Pintassilgo [2003], Pintassilgo et al. [2008], Pintassilgo and Lindroos [2008]). Game theoretic treatments of (marine) protected areas have received less attention so far. Sanchirico and Wilen [2001] and Beattie et al. [2002] study strategic interaction, both between fishermen and between fishermen and policymakers. Sumaila [2002] devises a computational model of assigning an MPA as a differential game between two agents. Ruijs and Janmaat [2007] have studied the strategic positioning of MPAs. They consider two countries, the location of MPAs and the effect of different migratiory regimes in a differential game. Busch [2008] derives some general conditions from game theory for terrestrial transboundary reserves to be superior over isolated reserves. Our paper contributes to the literature as it considers the combination of multiple use of protected areas with multiple agents: we examine cooperation and defector incentives when multiple agents are present in a multiple use setting, i.e. by considering impacts on fisheries and nature conservation. Furthermore the fisheries MPA model is improved to accommodate the habitat enhancement effects of MPAs, and a conservation game is introduced, that uses standard ecological functions to model species richness and consequent conservation benefits.

In section two we present a game theoretic model that investigates the issue of multiple use MPAs in a multiple country setting by developing two separate models of MPAs in a multiple country setting: one model for the fisheries case and one model for the species conservation case. Next we link the separate models and investigate the impacts of this linkage of fisheries and nature conservation. In section three we provide a numerical example and section four concludes.

2 Model description

In our model we consider a regional sea, such as the North sea, that is completely claimed by a number of countries. These countries have divided the sea in Exclusive Economic Zones of equal size. In this sea there is only one fish species that is of commercial interest for fisheries, and this fish species consists of a single stock. The other fish species, as well as mammals and benthos have no commercial value, only existence value. We ignore effects of time and space, to focus exclusively on the basic mechanisms. Furthermore we are interested in the steady state and not so much in the path towards that steady state.

Our fisheries model describes optimal harvesting of fish by a number of countries in a common sea with a single stock. We analyze the impact of establishing an MPA in a context where each country has a fixed share in the fishing area. In the fisheries model the cost of the establishment of an MPA is a reduction in harvest proportional to the MPA size[1]. We assume that assigning an MPA from a fisheries' perspective incurs no costs other then the opportunity costs of forgone harvest. For simplicity monitoring and compliance costs are neglected. The gains of a country consist of an increase in the growth rate of the shared stock owing to an increase in habitat quality in the unfished area. Such an increase cannot be reached by conventional harvest restrictions because it would only reduce the overall fishing pressure but not release one area completely, from fishing pressures, to recover habitat. This habitat effect of MPAs is a public good since a single country bears the cost while all countries benefit.

The nature conservation model describes conservation efforts by a number of countries in the same common sea. We analyze the impact of the total size of an MPA on the number of species protected and the resulting costs and benefits. Each country's MPA is a contribution to the total protected area, but the added benefits derived from the extra species protected by this MPA accrue to all countries, making this another public goods issue.

2.1 The game on marine protected areas as fisheries management tool

Our fisheries model assumes that there is only one fish stock that is worth harvesting from a commercial point of view. Hence the set N of n symmetric countries optimizes the harvest from a single stock, ignoring other stocks and species. If countries cooperate they maximize the sum of their profits, if they defect they optimize their own profits. Country i's profits Π_i depend on the harvest and the incurred costs. We use a supply side model that assumes that the full harvest can be sold at a fixed price p[2]:

$$\Pi_i = pH_i - C_i \quad \forall i \in N \tag{1}$$

where H_i is the total harvest of country i and C_i are the total costs of country i.

We assume that countries are fishing a single fish stock that is uniformly mixed over the fishing grounds and we model the growth of the stock with a modified Schaefer production function. We assume that the sea is completely claimed by EEZ's and that all EEZs are of equal size. The total size of the sea is normalized to one, and consequently each country has an EEZ of size $1/n$. Each country's fishing ground is its EEZ.

In this model of the fisheries it is assumed that in equilibrium the harvest equals the growth of the fish stock. The size of the marine protected area affects both the harvest and the growth rate of the fish stock but for simplicity we assume that the location of the reserve does not matter.

The total growth of the fish stock is modeled with a modified logistic growth function scaled such that the carrying capacity equals one. Hence the maximum stock size is also one. This growth function is:

$$G(X,M) = R(M)X(1-X) \tag{2}$$

with $R(M)$ the internal growth rate of the stock, $0 \le X \le 1$, and $0 \le M \le 1$ the total area protected as marine reserve.

Setting aside a share of the fishing ground as a marine reserve has a positive effect on the growth rate R through enhancing the growth rate in the reserve. We model this enhancement as a coupled production function: the internal growth rate is r_b in the unprotected area and $(r_b + r_M)$ in the protected area. This assumption is based on increased recruitment that is achieved by increasing the spawning biomass through the absence of fishing in sensitive areas. Similar functional forms for marine protected area modeling have been used by e.g. Schnier ([2005a], [2005b]), who also modifies the growth rate and Armstrong [2007] who modifies the carrying capacity as an effect of MPAs. If we further assume that both stock and carrying capacity in the protected and unprotected area are proportional to area we get:

$$\begin{aligned} G(X,M) &= r_b(1-M)X\left(1-\frac{(1-M)X}{(1-M)}\right)+(r_b+r_M)MX\left(1-\frac{MX}{M}\right) \\ &= (r_b + r_M M)X(1-X) \\ &= \left(r_b + r_M \sum_i {}^{1}\!/_{n} M_i\right)X(1-X) \end{aligned} \tag{3}$$

with $0 \le M_i \le 1$ is the share of the MPA of an individual country's EEZ. The sum of individual MPAs multiplied with EEZ size equals the total MPA, because each EEZ is of size ${}^{1}\!/_{n}$. Consequently each individual MPA is scaled by its relative size in the sea such that the sum equals the total protected area M.

To model the harvest we use a modified Schaefer harvest function:

$$H = Q(M)EX = nQ(M_i)E_i X \tag{4}$$

with $Q(M)$ the catchability, E the total effort level and E_i the effort level of player i. In a standard Schaefer function catchability is a parameter, but in our model catchability is a decreasing function of M. We use the following functions for $Q(M)$ and $Q(M_i)$:

$$\begin{aligned} Q(M) &= q_o - q_M M \\ Q(M_i) &= (1/n)\, q_o - q_M\, (1/n)\, M_i \end{aligned} \tag{5}$$

where q_o is the original catchability and q_M is the catchability reduction caused by the protected area.

Costs are assumed to be constant per unit of effort:

$$C_i = c_E E_i \tag{6}$$

2.1.1 Full cooperation on MPAs for fisheries

When players fully cooperate they maximize the sum of total profits:

$$\max \Pi = \max \sum_{i \in N} \Pi_i \tag{7}$$

with Π the total profits.

To obtain the steady state of the model we set the total growth equal to the harvest and solve for the effort level[3]. Under full cooperation the harvest is equal to the growth:

$$H = G(M, X) \Rightarrow R(M)\, X\, (1 - X) = Q(M)\, EX \Leftrightarrow X = 1 - \frac{Q(M)\, E}{R(M)} \tag{8}$$

Using the harvest function from (4) and substituting the equilibrium stock given in (8) we get the objective function:

$$\Pi(E, M) = pH - c_E E = pQ(M)\, E \left(1 - \frac{Q(M)\, E}{R(M)}\right) - c_E E \tag{9}$$

with M the total size of the MPA. Taking the First Order Condition with respect to effort we obtain[4]:

$$\frac{\partial \Pi}{\partial E} = pQ(M)\left(1-2\left(\frac{Q(M)E}{R(M)}\right)\right) - c_E = 0 \tag{10}$$

If we substitute the equilibrium stock given in (8) back into equation (10), we get:

$$\underbrace{pQ(M)(2X-1)}_{\text{Marginal benefit}} - \underbrace{c_E}_{\text{Marginal cost}} = 0 \tag{11}$$

which displays the standard components of a FOC in a static fisheries model: the first part of the derivative is the marginal benefit: an increase in effort increases the catch if $X > \frac{1}{2}$, and this additional catch is valued at *p*. The second part is the marginal cost: an extra unit of effort costs c_E.

Similarly, the first order condition with respect to *M* is given by:

$$\frac{\partial \Pi}{\partial M} = \left(\frac{(q_o - q_M M)E}{(r_b + r_M M)}\right)\left(\left(\frac{pr_M (q_o - q_M M)E}{(r_b + r_M M)}\right) + 2pq_M E\right) - pEq_M = 0 \tag{12}$$

If we substitute the equilibrium stock given (8) in back into equation (12), we get:

$$\underbrace{pr_M (1-X)^2}_{\text{Marginal benefit}} - \underbrace{pq_M E(2X-1)}_{\text{Marginal cost}} = 0 \tag{13}$$

This clearly illustrates the effect of MPAs. The first part of the derivative is the marginal benefit of an MPA: an extra unit of protected area increases the growth and consequently the harvest by $r_M (1-X)^2$ which is in turn valued at *p*. The second part shows the marginal cost of such an area in the form of the forgone harvest in an extra unit of protected area, also valued at *p*.

Solving equation (10) and (12) simultaneously we get a cubic equation which can be factorized into a quadratic and linear part and solved:

$$
\begin{aligned}
&M^* = \frac{pq_o - c_E}{pq_M}, \quad E^* = 0 \\
&M^* = \frac{(2pq_o + c_E) r_M \pm \sqrt{c_E r_M \left(r_M (8pq_o + c_E) + 8pq_M r_b\right)}}{2pq_M r_M}, \\
&E^* = \frac{-(pq_o r_M + 2c_E r_M + pq_M r_b)\sqrt{c_E r_M \left(r_M (8pq_o + c_E) + 8pq_M r_b\right)} \pm \left(7pc_E q_o r_M^2 + 2c_E^2 r_M^2 + 7pc_E q_M r_b r_M\right)}{2c_E q_M \sqrt{c_E r_M \left(r_M (8pq_o + c_E) + 8pq_M r_b\right)} \pm (4pq_o r_M + c_E r_M + 4pq_m r_b)}
\end{aligned} \tag{14}
$$

The first solution is a corner solution, and depending on parameter values the other two may be corner solutions as well. To evaluate the influence of individual parameters on the equilibrium protected area we use the implicit function theorem and the first order conditions (10) and (12) to determine the signs of their derivatives. The derivatives are shown in appendix I, the signs in Table 1.

Table 1: Signs of the derivatives of equilibrium MPA under full cooperation with respect to parameters in the fisheries game

Derivative	$\partial M/\partial p$	$\partial M/\partial c_E$	$\partial M/\partial r_M$	$\partial M/\partial r_b$	$\partial M/\partial q_M$	$\partial M/\partial q_o$
Sign	+	-	Und.	-	-	Und.

Und. = Undetermined. All relations are derived from the implicit function theorem.Assumptions used for signs above: All parameters >0, 0≤*M*≤1, 0≤*Q*(*M*)≤1.

Most signs of the derivatives can be determined with exception of the derivatives with respect to r_M and q_o. The signs that can be determined have the expected sign. An increase in price of fish (p) would make harvesting more worthwhile, and thus the protected area is increased to increase the harvest. An increase in the cost of effort (c_E) makes a protected area more expensive because the protected area decreases the effectiveness of effort through the catchability. Therefore the protected area is decreased when cost of effort increases.

Similarly an increase in r_b or q_M decreases protected area as they make it less effective by increasing the harvest that has to be given up to protect an area. The signs of $\partial M/\partial r_M$ and $\partial M/\partial q_o$ are mainly determined by the difference between price of fish and cost of effort and the parameters q_M and q_o. If $p>>c_E$ and $Q(M)$ is not too small, both signs of the derivatives are positive. This is in line with expectations: if the price of fish is large relative to the cost of catching it, an MPA pays off: the added growth bonus and thus extra fish to catch is more valuable than the relative minor costs of extra effort needed to catch that fish. A larger growth bonus (r_M) makes the MPA more valuable, because it increases the extra available catch. Similarly a larger original catchability (q_o) makes the MPA even cheaper because the reducing effect on the harvest of the MPA is smaller.

2.1.2 The Nash equilibrium for MPAs for fisheries

In a Nash equilibrium each individual player wishes to maximize his own fisheries profits, given that other players also maximize their profits. We assume that the sum of the harvest of all players is equal to the growth. The stock expressed in terms of effort and marine protected area as they can be influenced by an individual player is:

$$\sum_i H_i(M_i, E_i) = G(M, X) \Rightarrow \sum_{i=1}^{N} \left(Q(M_i)E_i\right)X = R\left(M_i, M_j\right)X(1-X) \Leftrightarrow$$
$$X = 1 - \frac{Q(M_i)E_i + (n-1)Q\left(M_j\right)E_j}{R\left(M_i, M_j\right)} \ \forall i \in N, i \neq j \qquad (15)$$

with j all other players.

For a single player the optimization problem is then:

$$\max \Pi_i = \max\left(pE_i\left(1 - \frac{Q(M_i)E_i + (n-1)Q\left(M_j\right)E_j}{R\left(M_i, M_j\right)}\right) - c_E E_i\right) \quad \forall i \in N \qquad (16)$$

Maximizing the individual profit function in (16) is not the same as the open access regime. Even though countries only optimize their own effort, no new entrants area allowed, thus the rent is not driven to zero. The first order conditions with respect to E_i is:

$$\frac{\partial \Pi}{\partial E_i} = pQ(M_i)\left(1-\frac{Q(M_i)E_i+(n-1)Q(M_j)E_j}{R(M_i,M_j)}\right)-\frac{pE_iQ(M_i)^2}{R(M_i,M_j)}-c_E=0 \tag{17}$$

If we substitute the equilibrium stock given in (15) back into equation (17), we get:

$$\underbrace{pQ(M_i)\left(2X-1-\left(\frac{(n-1)Q(M_j)E_j}{R(M_i)}\right)\right)}_{\text{Marginal benefit}} - \underbrace{c_E}_{\text{Marginal cost}} = 0 \tag{18}$$

which displays the standard components of a FOC in a static fisheries model: the first part of the derivative is the marginal benefit: an increase in effort increases the catch if X is larger than ½ plus the catch of the other players, and this additional catch is valued at p. The second part is the marginal cost: an extra unit of effort costs c_E.

The FOC of the marine protected area in equation (16) results in:

$$\frac{\partial \Pi_i}{\partial M_i} = -\tfrac{1}{n} pq_M E_i\left(1-\frac{\left(\tfrac{1}{n}q_o-\tfrac{1}{n}q_M M_i\right)E_i+(n-1)\left(\tfrac{1}{n}q_o-\tfrac{1}{n}q_M M_j\right)E_j}{r_b+r_M\left(\tfrac{1}{n}M_i-\tfrac{n-1}{n}M_j\right)}\right)+ \\ pE_i\left(\tfrac{1}{n}q_o-\tfrac{1}{n}q_M M_i\right)\left(\frac{q_M E_i}{n\left(r_b+r_M\left(\tfrac{1}{n}M_i-\tfrac{n-1}{n}M_j\right)\right)}+\frac{r_M\left(\tfrac{1}{n}q_o-\tfrac{1}{n}q_M M_i\right)E_i+(n-1)\left(\tfrac{1}{n}q_o-\tfrac{1}{n}q_M M_j\right)E_j}{n\left(r_b+r_M\left(\tfrac{1}{n}M_i-\tfrac{n-1}{n}M_j\right)\right)^2}\right) \tag{19}$$

If we substitute the equilibrium stock given in equation (15) back into equation (19) we get:

$$\underbrace{pr_M(1-X)\left(1-X-\frac{(n-1)Q(M_j)E_j}{R(M_i)}\right)}_{\text{Marginal benefit}} - \underbrace{pq_M E_i\left(2X-1-\frac{(n-1)Q(M_j)E_j}{R(M_i)}\right)}_{\text{Marginal cost}} = 0 \tag{20}$$

which is similar to the full cooperation case but now includes terms for the other players. The first part of the derivative is the marginal benefit of an MPA: an extra unit of protected area increases the growth and consequently the harvest by $r_M(1-X)\left(1-X-\frac{(n-1)Q(M_j)E_j}{R(M_i)}\right)$ where the last term accounts for the amount harvested by the other players. The extra harvest is in turn valued at p. The second part shows the marginal cost of protected area in the form of the forgone harvest (again with a modifier for the other players) in that extra unit of protected area, also valued at *p*.

Solving equations (17) and (19) simultaneously for *n* symmetric players we get another cubic equation which can be factorized into a quadratic and linear part and solved:

$$
\begin{aligned}
&M_i^* = \frac{pq_o - nc_E}{pq_M},\ E_i^* = 0 \\
&M_i^* = \frac{\left(2pq_o + c_E n^2\right) r_M \pm \sqrt{\left(r_M\left(p\left(4c_E n(n+1)\right)\left(q_o r_M + q_M r_b\right) + c_E^2 n^4 r_M\right)\right)}}{2pq_M r_M} \\
&E_i^* = \frac{-\left(\left(2pq_o + c_E n^2 + c_E n\right) r_M + pq_M r_b\right)\sqrt{\left(r_M\left(p\left(4c_E n(n+1)\right)\left(q_o r_M + q_M r_b\right) + c_E^2 n^4 r_M\right)\right)}}{q_M\left(c_E n^2 + c_E n\right)\sqrt{\left(r_M\left(p\left(4c_E n(n+1)\right)\left(q_o r_M + q_M r_b\right) + c_E^2 n^4 r_M\right)\right)} \pm q_M\left(p\left(2c_E(n+1)^2\left(q_o r_M + q_M r_b\right)\right) + r_M c_E^2 n^3 (n+1)\right)} \pm \\
&\frac{\left(r_M\left(p\left(3c_E n^2 + 4c_E n\right)\left(q_o r_M + q_M r_b\right) + c_E^2 n^3 (n+1)\right)\right)}{q_M\left(c_E n^2 + c_E n\right)\sqrt{\left(r_M\left(p\left(4c_E n(n+1)\right)\left(q_o r_M + q_M r_b\right) + c_E^2 n^4 r_M\right)\right)} \pm q_M\left(p\left(2c_E(n+1)^2\left(q_o r_M + q_M r_b\right)\right) + r_M c_E^2 n^3 (n+1)\right)}
\end{aligned}
\tag{21}
$$

To evaluate the influence of individual parameters on the equilibrium protected area we applied the same procedure as under full cooperation, using the implicit function theorem and equations (17) and (19). The results are the same as for full cooperation (Table 2, and appendix I).

Table 2: Signs of the derivatives of equilibrium MPA under the Nash equilibrium with respect to parameters in the fisheries game

Derivative	$\partial M_i/\partial p$	$\partial M_i/\partial c_E$	$\partial M_i/\partial r_M$	$\partial M_i/\partial r_b$	$\partial M_i/\partial q_M$	$\partial M_i/\partial q_o$
Sign	+	-	Und.	-	-	Und.

Und. = Undetermined. Assumptions used for signs above: All parameters >0, 0≤M_i≤1, 0≤$Q(M_i)$≤1.

The difference between the protected area under full cooperation and under the Nash equilibrium is:

$$
M^{FC} - M^{N} = \frac{\sqrt{c_E r_M}\left(\sqrt{n}\sqrt{4p(n+1)\left(q_o r_M + q_M r_b\right) + c_E n^3 r_M} - \sqrt{8p\left(q_o r_M + q_M r_b\right) + c_E r_M}\right) - c_E r_M\left(n^2 - 1\right)}{2pq_M r_M} \tag{22}
$$

where M^{FC} is the total area set aside under full cooperation and M^N is the total area set aside under the Nash equilibrium. Unfortunately, given our previous assumptions (all parameters >0, and $n \geq 2$), the above difference is unclear on the effect of individual parameters on the difference between protected area under full cooperation and the Nash equilibrium. Two exceptions are the parameters r_b and q_o, both of which increase the difference. For other parameters we have to resort to simulations. The same holds for the difference in payoffs between full cooperation and Nash equilibrium[5].

2.2 The game on marine protected areas for conservation

Conservation is a main goal of marine protected areas. In this game we measure conservation success as the species richness attained in a marine protected area. We do not model the populations of all species independently but instead use the species-area relationship to determine the number of species that a reserve contains. The species-area relationship (SPAR) has first been put forward by Arrhenius [1921] and is a curve of the general form $S = kA^z$ with S the number of species, A the area and k and z two parameters. It is explained by either the passive-sampling effect (MacArthur and Wilson [1967]) or the habitat diversity hypothesis (Williams [1943]).

The use of this relationship has been criticized for its scale-independent application and extrapolation (Leitner and Rosenzweig [1997], Rosenzweig [2005]), and its ambiguous role in conservation decisions in the Single Large or Several Small (SLOSS) debate (Simberloff and Abele [1976]). Despite these criticisms SPARs can still be used as a predictor of local species richness, if one accounts for the scale (Neigel [2003], Rosenzweig [2005]). Furthermore even though SPARs may support either several small reserves or a single large reserve, depending on parameters, in our case we assume a uniform sea, implying that the same species would be protected in several small reserves, and therefore we apply a SPAR on a single large reserve[6].

For mathematical convenience we transform the species-area relationship into a log-log relationship, i.e. $\ln S = \ln k + z \ln A$. We further assume that costs rise linear with the area set aside and that countries benefit from the (log) number of species in the total area set aside. Each country has an incentive to set some area aside, but given that the others will also set aside some area in a Nash equilibrium, each will set aside less. Assuming that all areas are interlinked and hence form one big conservation protected area, the total benefits of species conservation are:

$$BD(M) = b_P\left(\ln(S)\right) - c_P M = b_P\left(\ln(k) + z\ln(M)\right) - c_P M \qquad (23)$$

Here b_P represents the marginal global benefits from the protection of the log number of species, ln S, k and z are the parameters of the species area curve and c_P is the cost of protecting an area, such as monitoring and enforcement costs or opportunity costs for other uses.

2.2.1 Full cooperation on MPAs for nature conservation

Under full cooperation global welfare is maximized, accounting for benefit generation in all countries. The countries maximize:

$$BD(M) = b_P\left(\ln(k) + z\ln(M)\right) - c_P M \qquad (24)$$

with M again the total protected area. This results in the following first order condition:

$$\frac{b_P z}{M} - c_P = 0 \Leftrightarrow M^* = \frac{b_P z}{c_P} \qquad (25)$$

The full cooperation optimal MPA size is independent of the number of players, as they consider the protection of the full sea, and only one optimum exists, although the solution is silent on how this should be reached. Given symmetric costs and benefits a fair solution would be for all countries to have an MPA of size $\frac{1}{n}M^*$, resulting in a total protected area of M^* for the whole area.

2.2.2 The Nash equilibrium for MPAs for nature conservation

In a Nash equilibrium, each country maximizes its private welfare function, assuming all other countries also maximize their private welfare functions. We assume each country gets benefits proportional to their EEZ size, 1/*n*. Hence the global marginal benefits of protection accrue to the players in equal shares. Each country hence maximizes:

$$BD_i\left(M_i\right) = \tfrac{1}{n} b_P \left(\ln\left(k\right) + z\ln\left(\tfrac{1}{n}M_i + \tfrac{n-1}{n}M_j\right)\right) - c_P \tfrac{1}{n} M_i \quad \forall i \in N \tag{26}$$

For an interior solution, the first order condition becomes:

$$\frac{b_P z}{M_i + \left(n-1\right)M_j} - c_P = 0 \Leftrightarrow M_i^* = \frac{b_P z - c_P\left(n-1\right)M_j}{c_P} \qquad \forall i \in N \tag{27}$$

Again we see the strategic setting of the game from the first order condition. The additional benefit of an extra unit of area is in nominator, but it is scaled by the total area already protected. The costs of protecting one unit extra are $(1/n)c_P$.

Solving the FOC for M_i^* for *n* players simultaneously, for a symmetric solution we get:

$$M_i^* = \frac{b_P z}{n c_P} \tag{28}$$

which goes to zero for $n \to \infty$ clearly illustrating the suboptimality of this Nash equilibrium.

The difference in MPA assigned between the full cooperation and the Nash equilibrium is:

$$M^{FC} - M^{N} = \frac{b_P z}{c_P}\left(1 - \frac{1}{n}\right) \tag{29}$$

The difference in MPA size between the full cooperation case and the Nash equilibrium is increasing both in the number of players and in the gains of the MPA. The difference in payoff between full cooperation and the Nash equilibrium is:

$$W^{FC} - W^{N} = \frac{b_p z}{n}\left(\ln(n) - 1 + \frac{1}{n}\right) \tag{30}$$

For the gains of an MPA we see a similar pattern: the difference increases with the gains of a protected area. If we look at the number of players however, we see that if $n \rightarrow \infty$ the difference becomes 0. This is because the fixed payoff from a protected area under full cooperation has to be divided over a large number of players, leaving almost nothing for each individual player, whereas each player assigns a very small protected area under the Nash equilibrium, with both little revenues and costs.

Consequently if we assume that cooperation is easier if the differences in assigned size are smaller and differences in payoff are smaller, in the nature conservation case changes of cooperation decrease with increasing payoff of MPAs (i.e. an increase in b_p or z or a decrease in c_P). If the number of players increases to a very large number however, cooperation may become easier, although not necessarily so as the difference in assigned MPA becomes larger even though the payoffs become similar.

2.3 Combining the games

Marine protected areas affect fisheries as well as nature conservation. In order to see how the equilibria change if we take both into account, we now couple the games. If we combine the two games, the payoff functions of both countries change. The optimal MPA size, both from a Nash perspective and full cooperation's perspective may change as well, since we now add the two functions together. Formally, this is not issue linkage as in e.g. Folmer, van Mouche and Ragland ([1993]), Barrett ([1997]) and Buchner et al. ([2005]), because we are not dealing with two separate problems that are addressed with two different strategic instruments but with two separate problems that are addresses with one instrument: the size of the MPA.

When countries combine both problems the objective function under full cooperation becomes:

$$W\left(E,M\right)=pQ\left(M\right)E\left(1-\frac{Q\left(M\right)E}{R\left(M\right)}\right)-c_E E\ +b_P\left(\ln\left(k\right)+z\ln M\right)-c_P \tag{31}$$

Whereas the objective function of an individual country is:

$$\begin{aligned} W_i\left(E_i,M_i\right)=pE_i\left(1-\frac{Q\left(M_i\right)E_i+\left(n-1\right)Q\left(M_j\right)E_j}{R\left(M_i,M_j\right)}\right)-c_E E_i+ \\ {}^1\!/_n b_P\left(\ln\left(k\right)+z\ln\left({}^1\!/_n M_i+{}^{n-1}\!/_n M_j\right)\right)-{}^1\!/_n c_P M_i \qquad \forall i\in N \end{aligned} \tag{32}$$

The first order conditions of both problems are respectively:

$$\frac{\partial W}{\partial M}=\left(\frac{\left(q_o-q_M M\right)E}{\left(r_b+r_M M\right)}\right)\left(\left(\frac{pr_M\left(q_o-q_M M\right)E}{\left(r_b+r_M M\right)}\right)+2pq_M E\right)-pEq_M+\frac{b_P z}{M}-c_P=0 \tag{33}$$

$$\begin{aligned} \frac{\partial W\left(M_i\right)}{\partial M_i}=pE_i\left(\frac{q_M\left({}^1\!/_n q_o-{}^1\!/_n q_M M_i\right)E_i+\left(n-1\right)\left({}^1\!/_n q_o-{}^1\!/_n q_M M_j\right)E_j}{\left(r_b+r_M\left({}^1\!/_n M_i-{}^{n-1}\!/_n M_j\right)\right)}-\frac{q_M}{n}\right)+ \\ pE_i\left(\frac{\left({}^1\!/_n q_o-{}^1\!/_n q_M M_i\right)q_M E_i}{n\left(r_b+r_M\left({}^1\!/_n M_i-{}^{n-1}\!/_n M_j\right)\right)}+\frac{r_M\left({}^1\!/_n q_o-{}^1\!/_n q_M M_i\right)^2 E_i+\left(n-1\right)\left({}^1\!/_n q_o-{}^1\!/_n q_M M_j\right)E_j}{n\left(r_b+r_M\left({}^1\!/_n M_i-{}^{n-1}\!/_n M_j\right)\right)^2}\right) \\ +\frac{\left({}^1\!/_n\right)^2 b_P z}{{}^1\!/_n M_i+{}^{n-1}\!/_n M_j}-{}^1\!/_n c_P=0 \qquad \forall i\in N \end{aligned} \tag{34}$$

In these two FOC we recognize the first order conditions of the separate problems. The first order conditions with respect to effort are of course the same as under (10) and (18). Solving (10) and (18) for effort and substituting the results into (33) and (34) yields two quartic equations that cannot be solved analytically. The derivatives with respect to parameters that can be determined with the implicit function theorem are also inconclusive on the effects of parameters, unless we assume specific values. Therefore we have to resort to simulations.

The effect of the combination is a combined MPA that is an average between the equilibrium MPAs of the separated games. As the two separate games are completely separate except for the number of players (no parameters of one game occur in the other) and both are similar public good games it stands to reason that the combined game suffers from the same flaws, i.e. it is another public goods game. That does not mean that its externalities are as bad as in the separate games. As the combined game is an average the Nash equilibrium is better then the Nash equilibrium of one of the games. We now show the effect of these combined functions in a numerical example.

3 Numerical example

We now present a numerical example with two countries, as an illustration of the more general case. Suppose we have a sea that is fully claimed by EEZs and shared equally between two countries. Initial parameter settings are shown in table 3. The current parameter values are selected to illustrate the functioning of the model and in a sensitivity analysis we study the impacts of deviation from these parameter values.

Table 3: Arbitrary parameter values for the numerical example

Parameter		Value	Unit
p	Price	25	Euro per unit of harvest
c_E	Cost per unit of effort	5	Euro per unit of effort
r_b	Basic growth rate	0.2	-
r_M	Growth rate change MPAs	0.8	-
b_p	Benefits of protection	1	Euro per log of species number

k	Species-area curve constant	1.5	-
z	Species-area curve exponent	0.2	-
c_P	Costs of protection	0.25	Euro per unit of MPA

3.1 Fisheries: Full cooperation versus Nash

Solving the countries' maximization problem for M and X, for the given parameters using (10) and (12) gives a value of 38.6% for the total area. How this is distributed is not relevant from the full cooperation's perspective, it can be 38.6% for both countries or 77.2% in one country and none in the other or any other combination that generates 38.6% of the total area protected. A logical choice would be to share everything equally and set 38.6% of the area apart in both countries.

In Nash equilibrium the countries optimize their private income. We have plotted the two response functions in Figure 1. As can be seen from the figure the size of MPA share each country sets apart is much smaller than under full cooperation. Each country designates about 11.2% as MPA, and hence 11.2% of the total area is protected. Table 4 shows the outcomes per country under full cooperation and in a Nash equilibrium.

Table 4: Full cooperation vs. Nash Outcome for a single player

Variable	Full cooperation	Nash
M	38.6%	11.2%
Π	0.72	0.24
H	0.057	0.034
X	0.66	0.63

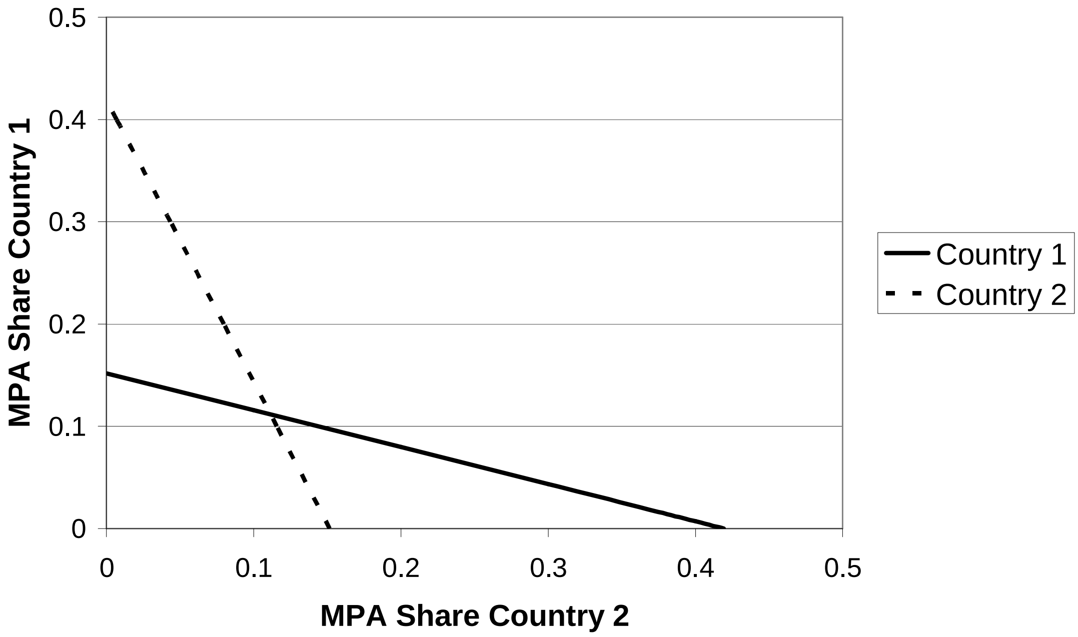

Figure 1: MPA sizes (in share of EEZ) of countries 1 and 2 as a function of the MPA size (in share of EEZ) in the other country and the resulting Nash equilibrium of the fisheries game

As can be seen from the table the outcomes of the full cooperation are much more favorable for both countries than playing Nash, but unless a social planner steps in or they reach some agreement by bargaining the Nash outcome is going to prevail.

3.2 Conservation: Full cooperation versus Nash

The conservation game for a two player game is similar to the fisheries game. Since the response functions have a slope of -1 in the symmetric case, the curves overlap completely implying an infinite number of Nash equilibria. If we enforce symmetry in the outcomes as is done in (28), we are left with one Nash equilibrium. Applying the formulas (25) and (28) and the parameter values from table 1 we get MPA sizes of 0.4 and 0.8 for the Nash equilibrium and full cooperation, respectively. To illustrate the prisoner's dilemma of the countries, the corresponding payoffs of full cooperation, Nash equilibrium and their combination are shown in Table 5.

The table shows that the game is a basic prisoner's dilemma. If the two countries manage to coordinate their actions they increase society's total welfare, but the full cooperation scenario will not be reached since both countries can increase their own payoff by defecting. The game shown here, however, does not show the full picture, the current prisoner's dilemma may be less severe if both countries take a combined perspective as is shown in the next section.

Table 5: Payoffs in the conservation game

		Country 2	
		Cooperate	Defect
Country 1	Cooperate	0.08, 0.08	0.01, 0.11
	Defect	0.11, 0.01	0.06, 0.06

3.3 Coupling both games

If we couple the games we get the objective functions as shown in section 2.3. For the parameter values given in Table 3 we get the response functions as shown in Figure 2. The Nash equilibrium (as can be seen from the figure) is at an MPA of 16%, whereas the full cooperation's optimum lies at 40%.

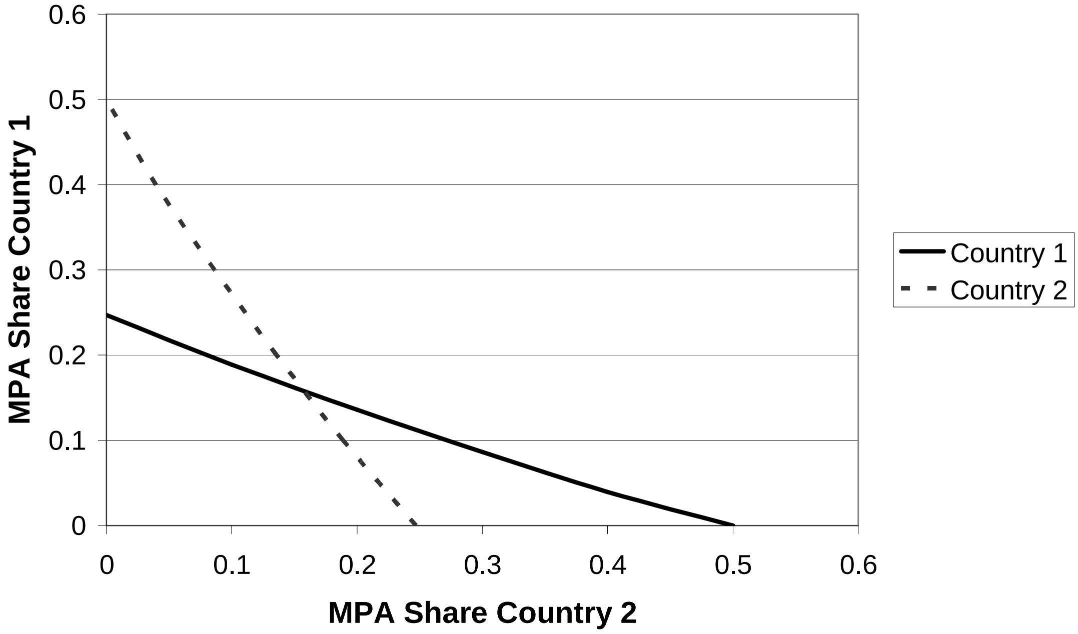

Figure 2: MPA sizes (in share of EEZ) of countries 1 and 2 as a function of the MPA size (in share of EEZ) in the other country and the resulting Nash equilibrium of the combined games

In table 6 some results are shown to compare the full cooperation's outcome with the Nash equilibrium. The results are similar in the sense that in the combined case the Nash equilibrium is clearly not preferred from the point of view of society, but in absence of a social planner, side payments or other mechanisms this is where society will end up if countries do not internalize the positive externalities.

Table 6: Full cooperation vs. Nash outcomes for a single player in the combined game

	Full cooperation	Nash Equilibrium
M	40%	16%
W_i	0.78	0.25
Π_i	0.72	0.25
BD	0.06	0
ln S	0.22	0.04
H	0.06	0.04

X	0.67	0.65

In figure 3 we show the payoff to a player from assigning an MPA share, given that the other player plays the optimum of the same strategy, and we marked the respective Nash and Full cooperation equilibria of the separate fisheries and conservation games. Figure 3 illustrates the suboptimality of considering the problem of MPA size in isolation. In this particular case the MPA from a pure fisheries perspective is to low and from a conservation perspective to high compared to the optimal MPA that takes both into account. It is therefore imperative to combine the two, since in special cases only, when the optimal fisheries and conservation MPA size coincide, the actual optimum is the same in the combined function and the separate games.

Another interesting finding in figure 3 is that from a society's point of view cooperation on a single issue can be worse than playing Nash on that single issue. Consider the payoff in the equilibrium where countries cooperate only on species conservation. We can see from figure 3 that it is actually lower than the payoff of the Nash equilibrium of conservation. If the cooperative solution from the conservation game is applied the losses of the fisheries are so large that they undo all the gains from conservation. Whether this happens of course depends on parameter values, but the possibility is enough to demonstrate the necessity of considering multiple uses in this multiple country setting.

As stated before since the externalities run in the same directions in both games combining the games does not remove defection incentives. What we can see from figure 3 is that from a fisheries point of view combining the games constitutes an improvement. Furthermore the difference between the social optimum and the Nash equilibrium has also become smaller giving at least some improvement.

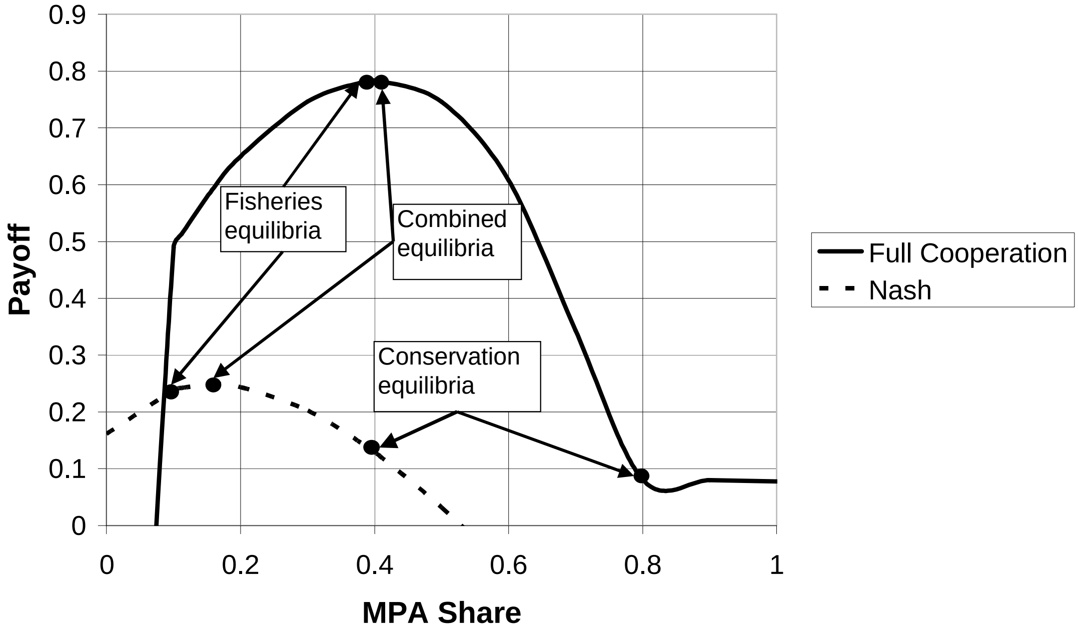

Figure 3: The total payoff of one country and the respective equilibria of the isolated games, as a function of a) the MPA size chosen by both countries (as a share of EEZ) under full cooperation, b) the MPA size chosen by one country (as a share of EEZ) assuming that that the other player plays Nash. For parameter values see table 3.

3.4 Sensitivity analysis

To illustrate the model further and provide some more insights into the incentives for cooperation we have carried out a sensitivity analysis all the parameters in the combined model. For each parameter we calculated the values of MPA share and payoff for the change of a single parameter in steps of 10%, over a range of minus 50% to plus 50%, while keeping the other parameters fixed. We used the same procedure for the fisheries model to calculate the effect of parameters on the difference between full cooperation and Nash equilibrium because these differences could not be analyzed analytically.

3.4.1 Differences between full cooperation and Nash equilibrium in the fisheries game

In Figure 4 we show how the absolute difference between full cooperation and Nash equilibrium in the fisheries game both for the payoff ($\Pi_i^{FC} - \Pi_i^{N}$) and MPA share($M^{FC} - M^{N}$), as a result of changing the price of fish (p) and changing the growth bonus in the MPA (r_M), given that all other parameters remain on the base level. The graphs for the other parameters are in Appendix II and the relation between the difference between full cooperation and Nash equilibrium in payoff and MPA share as a function of parameters are in table 7.

Table 7: The relation between parameters and the difference between full cooperation and the Nash equilibrium for payoff and MPA share in the fisheries game

	p	c_E	r_b	r_M	q_o	q_M
M_i	-	+	+	-	+	-
W_i	+	-	+	+	+	-

A "+" indicates that the parameter and difference move in the same direction, a "-" indicates that the parameter and difference move in opposite directions.

The effect of parameters on the difference between full cooperation and Nash equilibrium varies. Assuming that cooperation becomes more likely when this difference is smaller, shows that only parameter q_M has an unequivocal diminishing effect on these differences, when it increases. All other parameters increase either the difference in payoff or the difference in MPA share (table 7).

The same effect can be seen in Figure 4 for two specific parameters: if the price of fish (p) increases, the value of the harvest increases and this drives up the payoff under cooperation more than it drives up the payoff under the Nash equilibrium, hence the increasing difference in payoff. The incentive to set aside more area as

MPA is also larger even under the Nash equilibrium and thus the difference in total area set aside decreases.

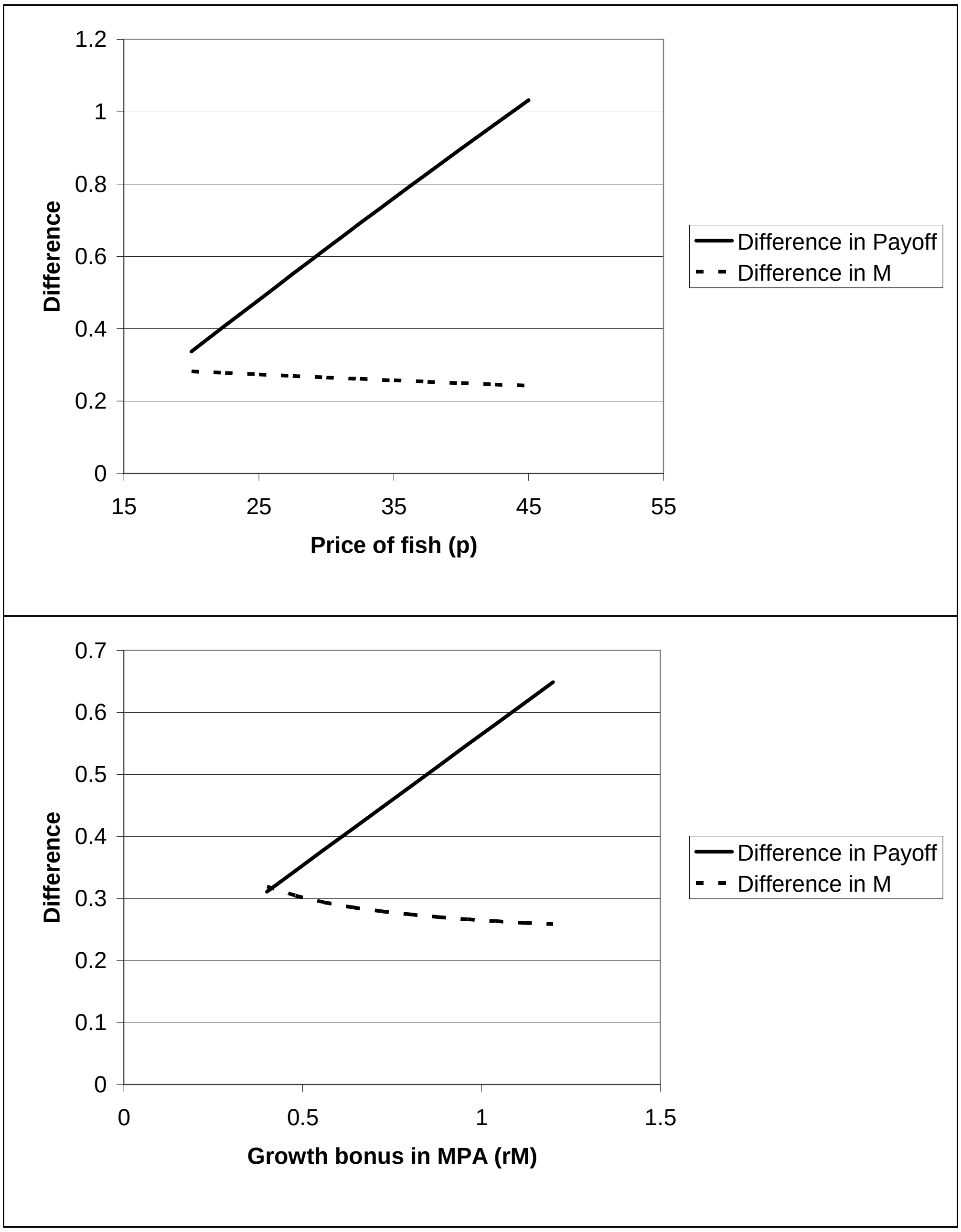

Figure 4: The difference between full cooperation and Nash equilibrium in payoff and MPA share, as a function of changing parameters.

The same holds for the growth bonus in the MPA (r_M). If r_M increases the payoff of the MPA becomes larger, but this payoff is reaped to a larger extent under full cooperation hence the increase in the payoff difference. The growth bonus also increases the incentives to set aside MPA, so the size assigned under the Nash equilibrium becomes relatively larger decreasing the difference with full cooperation in MPA size assigned.

3.4.2 Sensitivity analysis of the combined game

In Figure 5 we show how payoff and MPA share change as a result of changing the reduction in catchability (q_M) and changing the curvature of the species-area curve (z), given that all other parameters remain on the base level. The graphs for the other parameters are in Appendix II and the relation between parameters and payoff and MPA share are in table 8.

Table 8: The relation between parameters, payoffs and MPA share

	p	c_E	r_b	r_M	q_o	q_M	b_g	z	c_P
M_i	+	-	-	+	+	-	+	+	-
W_i	+	-	+	+	+	-	+	-	-

A "+" indicates that the parameter and variable move in the same direction, a "-" indicates that the parameter and variable move in opposite directions.

Increasing q_M causes both the MPA share and the payoff to decrease, and this decrease is larger for the full cooperation case than for the Nash equilibrium (Figure 5). If q_M increases an MPA becomes more expensive, because more harvest has to be given up per unit of protected area, hence the decrease. If we once again assume that cooperation is easier when there is less at stake, i.e. the differences between payoff and MPA share are smaller, then cooperation becomes more likely with increasing q_M.

Increasing the curvature of the species-area curve (z), causes the MPA share to increase but payoff falls, because we get the same benefit for more species. In Figure 4 we see that the effect of the z parameter, ceteris paribus, has little effect on the difference in equilibrium MPA between the full cooperation case and the Nash equilibrium. Hence the difficulty of reaching a social optimum stays just as hard in a less diverse environment as it is in a rich environment.

Overall the differences in payoff and MPA between the full cooperation case and the Nash equilibrium seem to become smaller only with decreasing gains of MPAs.

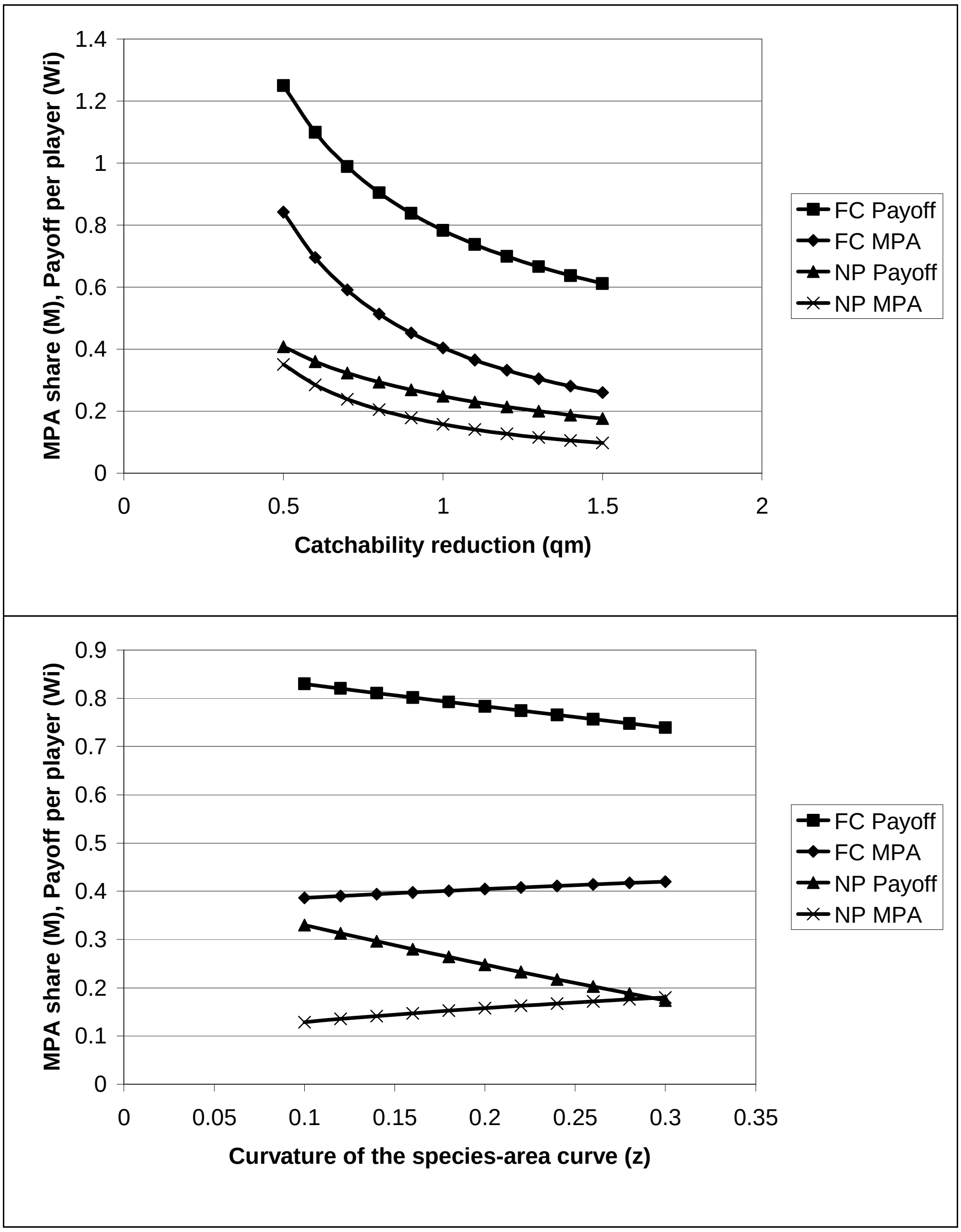

Figure 5: MPA and payoff under full cooperation (FC) and Nash equilibrium (NP) as a function of parameters q_M and z, keeping other parameters at the base level.

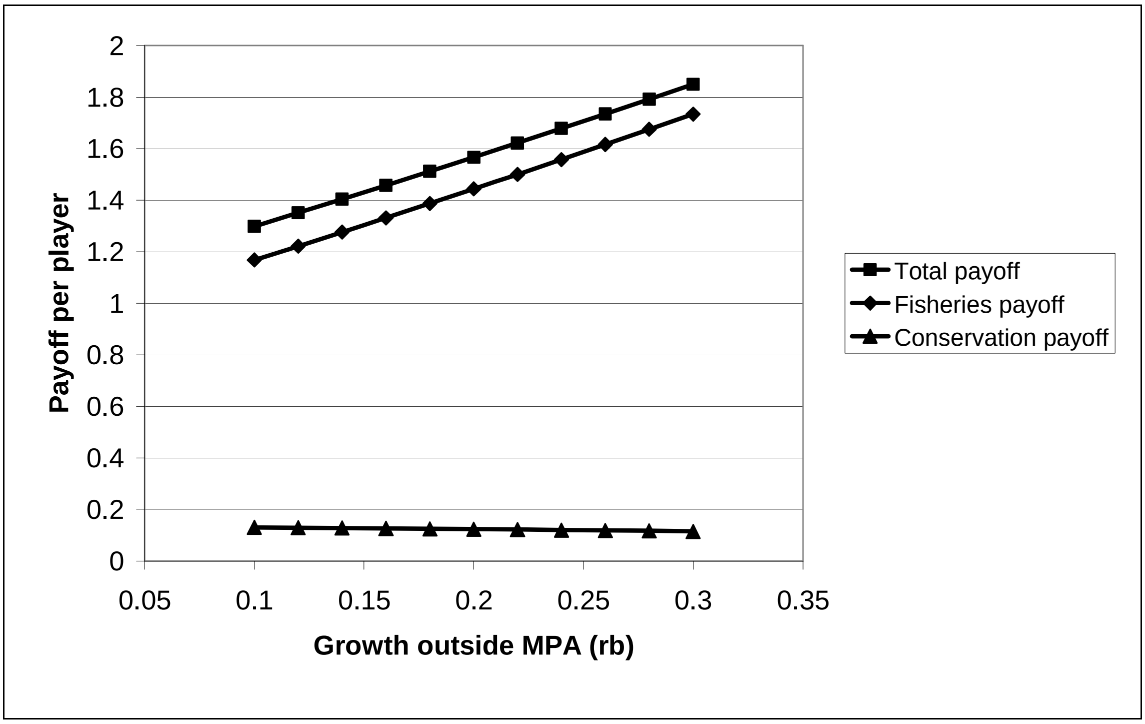

Figure 6: Payoff per player in total and from the separate games as a function of r_b, keeping other parameters at the base level.

Figure 6 provides intuition on the mechanisms in the model: increasing the growth outside the MPA decreases the necessity of an MPA from a fisheries perspective. Moreover it increases the harvest and consequently the payoff of the fisheries. Therefore the optimum of the combined game moves towards the fisheries optimum and away from the conservation optimum. As the optimum moves away from the pure conservation optimum, the profits of conservation fall slightly, but this is made up for by the fisheries profits. Increasing the growth outside the MPA consequently has the expected effect of weighing the fisheries interests heavier then before thus moving towards the fisheries optimum.

4 Discussion and conclusions

4.1 Main findings

We now present our main findings and then continue with some limitations of the study and suggestions for further research. In this paper we considered the effects of MPAs on fisheries and species conservation in a multi-country setting. We analyzed the resulting externalities and the possible shifts in equilibria if two separate games of MPA assignment are combined. We focused on the main issues and developed a model that contains some of the important aspects that arise in the multiple country, multiple use setting that MPA planners, and marine policy makers in general, face.

Although the separate games do not provide major new insights, the combination of the games provides a counterintuitive result: cooperation on a single issue may be worse than Nash if we take a combined perspective.

The setting of the fisheries model is such that if MPAs increase growth rates by more then the reduced harvest it pays to set aside some area. The results suggest that cooperation is better than Nash, but this is straightforward. Furthermore the results show that the difference in MPA size assigned between cooperation and Nash equilibrium reduces when either the growth bonus of MPA increases, or when the price of fish increases. However, the payoff difference between full cooperation and Nash equilibrium also increases with these parameters offering little scope for bargaining. If the catchability reduction of MPA increases both the difference in assigned MPA and payoff go down. Essentially if MPAs become worth less, the differences between full cooperation and Nash equilibrium decrease.

The conservation game offers a new approach to the conservation problem. Although game theory has been used to analyze transboundary parks in general

(Busch [2008]), to our knowledge species-area curves were never used specifically in a game. The results of the game are also straightforward: for species conservation cooperation is better than the Nash equilibrium, but that due to defector incentives we have a social dilemma. In contrast with the fisheries game the difference in MPA assigned as well as the difference in payoff between full cooperation and Nash equilibrium are increasing in both the gains of the MPA, and the number of players. Therefore it seems that achieving cooperation will be hard, unless there is little to be gained by assigning MPAs anyway.

The core result of the paper is that the combined game offers a new and counterintuitive perspective on these standard results of the separate games: if we take a combined view, cooperation on a single issue may be worse than the Nash equilibrium of that single issue. By ignoring the multiple use of the MPA the damage done to one of the uses is so large that it destroys all the gains from cooperation on the other issue. Therefore we conclude that accounting for multiple uses is not just a nicety of this model, but a necessity when planning MPAs.

Furthermore the combined game has better possibilities from society's perspective then the single games do. In our numerical example the combined game increases the MPA assigned compared to the fisheries case. Also it decreases the difference between full cooperation and Nash equilibrium compared to the biodiversity case. Unfortunately combining both games is not enough to overcome a prisoner's dilemma, but even a compromised combined Nash MPA may be better than cooperation on a single issue.

Summarizing, MPAs are a valuable tool for conservation and fisheries management in the EEZs. Optimal use of this tool, however, requires consideration of its multiple uses effects, if not then it might be better from society's point of view not to cooperate.

Although not a perfect solution The MSD (and other European marine policy) encourages countries to cooperate and more importantly, consider the full effects of their actions in their marine strategies. We conclude that MPAs may not be a panacea, but they will surely help in safeguarding our marine environment.

4.2 Limitations of the study

We restricted our analysis to symmetric players. The issue linkage models of Cesar and de Zeeuw [1996] and Folmer et al. [1993] asymmetry is a requirement to break the prisoner's dilemma. Their models consist of two prisoner's dilemmas that are completely reversed and hence they cancel each other out when linked. If we include asymmetry in our model it would not play as big a role since our model considers only one instrument, in contrast to the models of Cesar and de Zeeuw [1996] and Folmer et al. [1993] who consider two instruments. Even if one country would have a higher advantage in the fisheries and the other in species conservation we expect that the combined game would still give an average of the two. Where that average would be, depends on parameter values.

Although the fisheries model suggests a positive role for MPAs in fisheries management, this result may no longer hold, if open access is present, as demonstrated in Hannesson [1998] and Anderson [2002]. Even though agents may play a Nash equilibrium in our model, resulting in a suboptimal solution, open access does not occur since there are no potential new entrants (as the number of countries is given). Only if a large number of agents enter the fisheries the size of the MPA is driven to zero.

A further limitation of the model is the fact that the fisheries game does not include monitoring and compliance costs. A more realistic setting would include a set-aside cost in the fisheries case, equal to the one in the conservation case. In the combined case this compliance cost would then occur only once, implying a further advantage of combination.

4.3 Suggestions for further research

As pointed out in the introduction MPAs are a static tool in a dynamic environment. In further research it will be useful to explicitly include issues of time and space in addition to the steady state analysis of the current paper. The importance of spatial dynamics has been demonstrated by e.g. Ruijs and Janmaat [2007], but always just for the fisheries case and to our knowledge never for the combination of fisheries and conservation.

The evolution of species richness over time and space, is very complex and a constant source of debate among ecologists (see Gray [2001] for a critical review for the marine environment). The current approach is therefore a pragmatic compromise, but further empirical and theoretical work on this issue would greatly increase our understanding of the drivers within MPAs and facilitate the inclusion of conservation issues in the MPA and fisheries modeling debate.

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Appendix I: Derivatives with respect to parameters

We used the implicit function theorem and the relevant first order conditions to evaluate the effect of parameters on the equilibrium MPA. The equilibrium value of other variables was entered in the relevant FOC, before the derivative was determined.

If we substitute E^* calculated from (10) in first order condition (12) and rearrange we get:

$$\frac{\left(p\left(q_M M-q_o\right)+c_E\right)\left(pq_M^2 r_M M^2-\left(q_M r_M\left(2pq_o+c_E\right)\right)M+q_o r_M\left(pq_o-c_E\right)-2c_E q_M r_b\right)}{4p\left(q_M M-q_o\right)^3}=0 \tag{35}$$

We are only interested in the solution stemming from the quadratic part. Therefore we can determine the effect of parameters on the equilibrium MPA, by taking derivatives only on the part:

$$\left(pq_M^2 r_M M^2-\left(q_M r_M\left(2pq_o+c_E\right)\right)M+q_o r_M\left(pq_o-c_E\right)-2c_E q_M r_b\right)=0 \tag{36}$$

This results in the following derivatives:

$$\frac{\partial M}{\partial p}=\frac{-\left(q_M M-q_o\right)^2}{q_M\left(2p\left(q_M M-q_o\right)-c_E\right)} \tag{37}$$

$$\frac{\partial M}{\partial c_E}=\frac{r_M\left(q_M M+q_o\right)+2q_M r_b}{r_M q_M\left(2p\left(q_M M-q_o\right)-c_E\right)} \tag{38}$$

$$\frac{\partial M}{\partial r_M}=\frac{c_E\left(q_M M+q_o\right)-p\left(q_M M-q_o\right)^2}{r_M q_M\left(2p\left(q_M M-q_o\right)-c\right)} \tag{39}$$

$$\frac{\partial M}{\partial r_b}=\frac{2c_E}{r_M\left(2p\left(q_M M-q_o\right)-c_E\right)} \tag{40}$$

$$\frac{\partial M}{\partial q_M}=\frac{c_E\left(r_M M+2r_b\right)-2pr_M M\left(q_M M-q_o\right)}{r_M q_M\left(2p\left(q_M M-q_o\right)-c_E\right)} \tag{41}$$

$$\frac{\partial M}{\partial q_o} = \frac{2p\left(q_M M - q_o\right) + c_E}{q_M\left(2p\left(q_M M - q_o\right) - c_E\right)} \tag{42}$$

The procedure for the derivatives in the Nash equilibrium is similar: calculate E_i^* from equation (17), insert it into equation (19), both for E_i^* and E_j^*, replace M_j^* with M_i^*, and take derivatives with respect to the quadratic part of the resulting cubic equation:

$$\frac{\left(pq_o - pq_M M_i - nc_E\right)\left(pq_M^2 r_M M_i^2 - 2pq_M q_o r_M M_i - c_E n^2 q_M r_M M_i + pq_o^2 r_M - c_E n q_o r_M - c_E n^2 q_M r_b - c_E n q_M r_b\right)}{p\left(n+1\right)^2\left(q_M M_i - q_o\right)^3} = 0 \tag{43}$$

This results in the following derivatives:

$$\frac{\partial M_i}{\partial p} = \frac{-\left(q_o - q_M M_i\right)^2}{q_M\left(2p\left(q_M M_i - q_o\right) - n^2 c_E\right)} \tag{44}$$

$$\frac{\partial M_i}{\partial c_E} = \frac{n\left(r_M\left(q_o + nq_M M_i\right) + \left(n+1\right)q_M r_b\right)}{q_M r_M\left(2p\left(q_M M_i - q_o\right) - n^2 c_E\right)} \tag{45}$$

$$\frac{\partial M_i}{\partial r_M} = \frac{c_E n\left(nq_M M_i + q_o\right) - p\left(q_M M_i - q_o\right)^2}{r_M q_M\left(2p\left(q_M M_i - q_o\right) - c_E n^2\right)} \tag{46}$$

$$\frac{\partial M_i}{\partial r_b} = \frac{n\left(n+1\right)c_E}{r_M\left(2p\left(q_M M_i - q_o\right) - c_E n^2\right)} \tag{47}$$

$$\frac{\partial M_i}{\partial q_M} = \frac{c_E n\left(nr_M M_i + nr_b + r_b\right) - 2pr_M M_i\left(q_M M_i - q_o\right)}{r_M q_M\left(2p\left(q_M M - q_o\right) - c_E n^2\right)} \tag{48}$$

$$\frac{\partial M_i}{\partial q_o} = \frac{2p\left(q_M M_i - q_o\right) + nc_E}{q_M\left(2p\left(q_M M - q_o\right) - c_E n^2\right)} \tag{49}$$

Appendix II: Difference between full cooperation and Nash equilibrium in the fisheries game

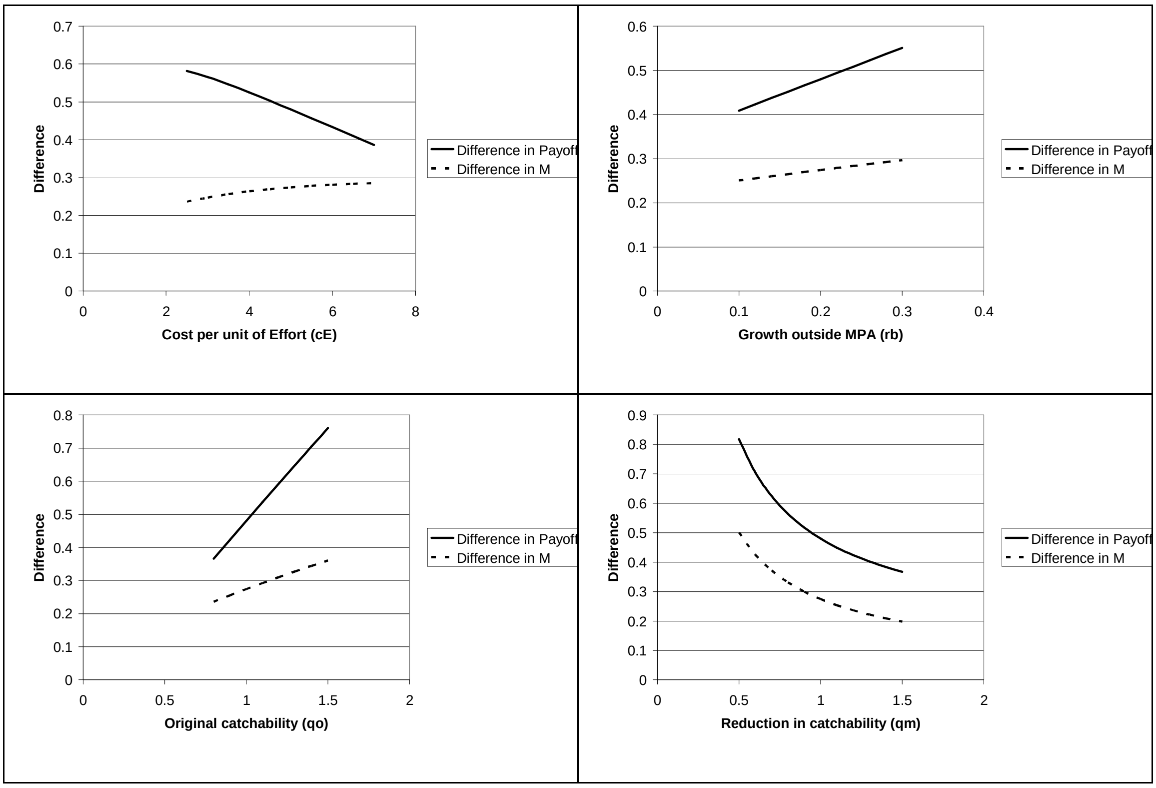

Figure 7: Difference between full cooperation and Nash equilibrium in payoff and MPA share as a function of changing parameters

Appendix III: Figures of payoff and MPA share as a function of changing parameters

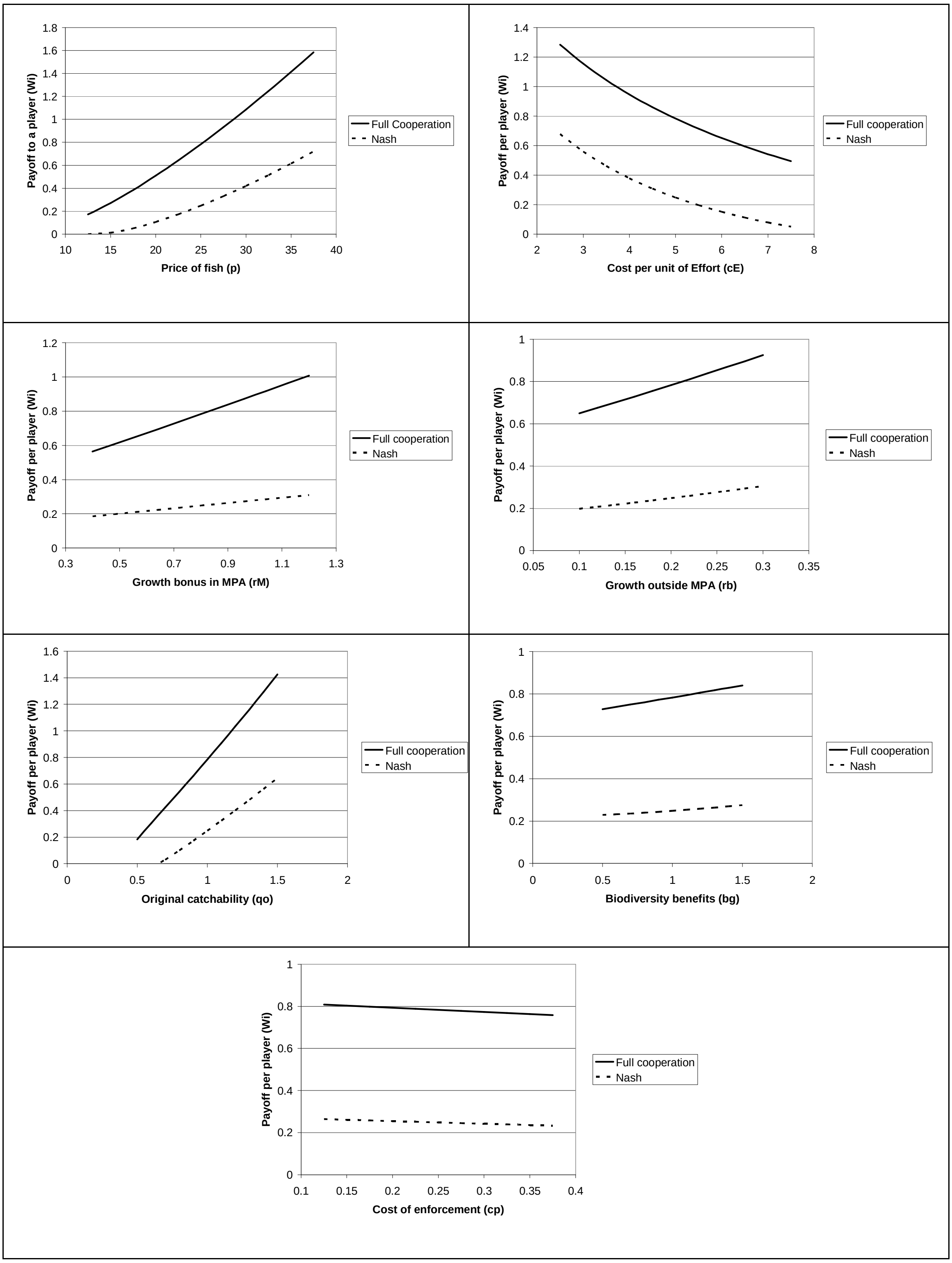

Figure 8: Payoff per player under full cooperation and Nash as a function of changing a parameter in the model.

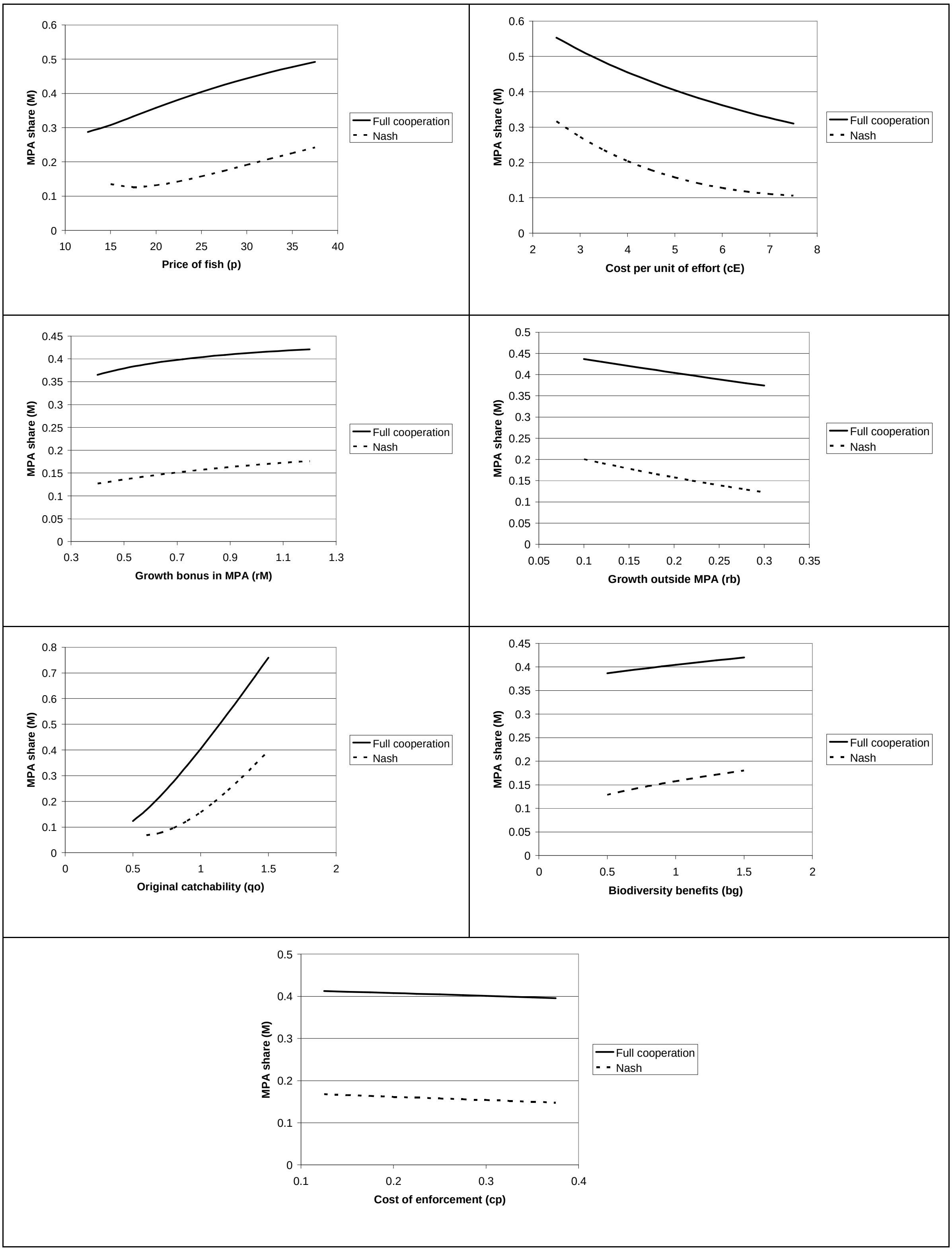

Figure 9: MPA share under full cooperation and Nash as a function of changing a parameter in the model.

[1] In the current model setting we assume a direct proportionality between reduction in harvest and MPA size. In further research other specifications such as concave or convex reductions can be explored. However, such specifications would not alter the basic line of reasoning.

[2] In this model we denote parameters with lower case and variables with capital letters.

[3] The model can also be solved in terms of stock. We chose to use effort here because the solutions are more straight forward, but will occasionally substitute stock.

[4] We present only the interior solutions of the model, although corner solutions may occur depending on parameter values. Corner solutions arise if the bounded variables such as stock and marine protected area size exceed their bounds under the interior solution.

[5] The difference in payoff is a complex and long expression, shedding no light on the effect of parameters, therefore we do not show it here. It is available from the authors upon request

[6] In a more elaborate analysis a more complex specification on the relation between area, species richness and the benefits of nature conservation can be used. However, this would not change the fundamentals of the current analysis.