On Species Preservation and Non-Cooperative Exploiters

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Abstract

Game-theoretic fisheries models typically consider cases where some players harvest a single common fish stock. It is, however, the case that these types of models do not capture many real world mixed fisheries, where species are biological independent or dependent. The present paper considers cases where several non-cooperative exploiters are involved in mixed fisheries. This paper is targeting biodiversity preservation by setting up a two species model with the aim of ensuring both species survive harvesting of exploiters adapting a non-cooperative behaviour. The model starts out as a multi-species model without biological dependency and is then modified to include also biological dependency. We contribute to the literature by analytically finding the limits on the number of players preserving both species including the conditions to be satisfied. For visual purposes we simulate a two species model with different kind of interrelationship.

Key words: Biodiversity preservation, non-cooperative game, multi-species fisheries, bio-economic modelling.

JEL Codes C70, Q22, Q28.

1. Introduction

Game-theoretic fisheries models typically consider cases where some limited number of countries harvest a single common fish stock. In real world fisheries, countries does, however, often exploit several stocks simultaneously in mixed fisheries where the stocks may or may not be biologically dependent. This paper seeks to analyse the biodiversity preservation with the aim of avoiding extinction of the species when non-cooperative exploiters harvest in a multi-species fisheries.

Hannesson (1983) presented a general multi-species model with interdependent fish species and studied optimal exploitation of two-species predator-prey fisheries. He examined how the optimal exploitation in a Lotka-Volterra type of model with costless harvesting and the impact on the optimal exploitation of increasing discount rate. Mesterton-Gibbons (1988) investigates the optimal policy in a theoretical setting for combining harvesting of predator-prey. Fischer and Mirman (1996) have studied strategic interaction in multi-species fisheries also in a theoretical model, whereas Sumaila (1997) has studied the case of Barents Sea fisheries. Many of these papers have investigated the optimal policies, corresponding to the joint action by the exploiters of the multi-species. From traditional game theoretical analysis of single species fisheries, we know that, full cooperation may be hard to achieve due to free-rider incentives (Kronbak & Lindroos 2007). We therefore find there is a lack in the literature studying the other branch of the game theoretical behaviour, namely the non-cooperative or the Nash equilibrium, in a two-species setting. The present paper is the first to consider the number of agents that can be sustained in a non-cooperative equilibrium without driving one stock to extinction. We seek to answer questions as; What are the driving force for species extinction in a two-species model with biological dependency? The opposite effect of the tragedy of the commons is the increased usefulness of a resource as the result of many individuals using it. This effect is often referred to as the 'comedy of the commons (Rose 1986). Does 'Comedy of the Commons' occur, and when, in two-species fisheries? An finally most important, what are the ecosystem consequences of economic competition?

Our modeling approach is to consider two species first biologically independent species and later biologically dependent species. The case with bilogical independent species is determined as a point of reference. We seek the static optimal harvesting effort in both cases and apply this as a baseline. In both cases, we gradually increase the number of agents until we face the conditions for optimal exploitation for a limited number of symmetric competitive exploiters with non-selective harvesting technology. We relate the optimal competitive effort levels to the species biotechnical productivity and contribute to the literature by finding conditions for stability and exploitation of stocks in a two species model with biological dependent species, where it is no longer sufficient to apply the biotechnical productivity. Our methodology allows us to relate the number of competitive exploiters to the extinction of the species. We illustrate our results in a simulation model.

In Section 2, we introduce the model by identifying a single stock and several exploiters. In Section 3, we have a two-species fishery with 2 countries exploiting these biological independent species. In section 4 set up the model with two-species fishery with 2 countries exploiting biological dependent species. In section 5 we simulate the analytical results from section 4. Finally, Section 6 concludes and discusses future research issues.

2. Basic one stock model

Consider a game between n agents harvesting a common natural resource, x (Mesterton-Gibbons 2000). Assume equilibrium use of the fish stock over time by these agents:

$$\frac{dx}{dt} = F(x) - \sum_{i=1}^{n} h_i = 0 . \tag{1}$$

The growth function is explicitly formulated as logistic growth:

$$F(x)=Rx(1-x/K). \tag{2}$$

Here R is the intrinsic growth rate of fish and K is the carrying capacity of the single stock in the ecosystem. The production function is assumed bi-linear in effort, E and stock:[1]

$$h_i=qE_ix,\ i=\{1,2,3,...n\}, \tag{3}$$

Where q is the catchability coefficient. It follows from (1) - (3) that the equilibrium fish stock is given as:

$$x=\frac{K}{R}(R-q\sum_{i=1}^{n}E_i). \tag{4}$$

Hence, the equilibrium stock decreases linearly in total effort.

If players adapt a traditional non-cooperative Nash game approach when determining their effort this corresponds to common pool exploitation, or a restricted open access, since the exploiters only consider finding a strategy combination from which no player has a unilateral incentives to depart (Mesterton-Gibbons 1993). The result is kind of a restricted tragedy of the commons (Hardin 1968),[2] with over-exploitation and partly dissipation of rents since players only consider own incentives and not the joint incentives.

If extinction of the species should occur, the biomass should be lower than some threshold. With a logistic growth function there is no positive threshold

1 We have assumed a simple Schaefer production function, a more advanced production function, for example a Cobb-Douglas production function, would complicatematters, and we would not be able to find analystical results.

2 If the number of players where infinite we would have the tragedy of the commons (Mesteton-Gibbons 1993).

and the critical depensation is zero. It would then be the case that extinction occur when the total effort exceeds the biotechnical productivity, R/q.

3. Multiple independent stocks

To examine the consequences of more players exploiting two biological independent stock, we start out by defining and solving for the solve owner solution. We then gradually increases the number of players to two, and then to *n*.

3.1. Sole owner optimum w/ two species

Let us consider two biologically independent species x_1 and x_2 each following a logistic growth function as described in (2). We then assume a sole owner harvesting, the two stocks with no possibilities for selectivity, thus the same effort reduces both stocks, which is reflected by identical catchability coefficient for the stocks.[3] The two biologically independent steady state equilibrium stocks are:

$$x_1 = K_1 - \frac{K_1 qE}{R_1}, \tag{5a}$$

$$x_2 = K_2 - \frac{K_2 qE}{R_2} \tag{5b}$$

where the sub-script is an indicator for the species.

The optimal fishing effort for the sole owner is derived from the following objective function:

3 One could also assume different catchability coefficients for the different stocks as long as the coefficients are constant over time, we have a joint production This would only require adding a subscript on the q's, but for simplicity this is not done. An extension of the model could be to allow for a certain degree of selectivity in the fishery.

$$\underset{E}{Max}\ p_1qEx_1 + p_2qEx_2 - cE\ , \tag{6}$$

s.t. eq. (5a) and (5b)

subject to the stocks being at equilibrium (5). Here p_1 is the market price of fish stock x_1, p_2 the market price of fish stock x_2 and c is the unit cost of effort.[4]

Assuming logistic growth for the two stocks, stocks are in steady state and using the first order condition (FOC), the optimal fishing effort for a sole owner exploiting two stocks is:

$$E^* = \frac{p_1qK_1 + p_2qK_2 - c}{\frac{2p_1q^2K_1}{R_1} + \frac{2p_2q^2K_2}{R_2}}\ . \tag{7}$$

Reinserting E^* into the equilibrium stocks yields the specific steady state stock levels. Note that in this model it may be optimal to drive one of the stocks to extinctions. This is the case if the optimal effort level exceeds a threshold defined by the biotechnical productivity, which is the ratio of the intrinsic growth rate and catchability coefficient, $E^* \geq R_j / q$, j={1,2} (Clark 1990). Since the optimal effort is defined by equation (7) extinction is particularly of concern if one of the stocks has a low biotechnical productivity and the cost-price ratio of other species is sufficiently low (Clark 1990). The optimal effort level is a trade off between harvesting the different species and their productivity. If the intrinsic growth rate of a species is increased then the optimal effort level is also increased. The trade off occurs when there is an increase in the carrying capacity or in the price of one of species. The change in the optimal effort level depends on whether the size of the intrinsic growth rate of the species is larger than the growth rate of the other species (then effort increases) or lower (then optimal effort decreases) (Clark 1990). With two species this is relatively simple to test, but with many species the results are more ambiguous.

4 We assume exogenously given prices of fish.

3.2. *The two-player equilibrium w/ two independent species*

If there are now two symmetric, competing countries harvesting two common species, then country *i* maximises the following:

$$\max_{E_i} p_1 q E_i x_1 + p_2 q E_i x_2 - cE_i \text{ , } i=\{1,2\}. \tag{8}$$

s.t. (5a) and (5b).

With the logistic growth functions and stocks in steady state, the reaction functions are derived from FOC (Ruseski 1998):

$$E_i = E^* - \frac{E_k}{2}. \tag{9}$$

Rearranging it becomes clear that the two-country equilibrium results in 4/3 higher effort than the sole owner case, since the equilibrium is:

$$E_i = \frac{2}{3} E^* = E_k \text{ ,} \tag{10}$$

Thus total effort, E_T=3/4E^*. The two-player equilibrium is now generalised into *n* player equilibrium exploiting two biologically independent species.

3.3. *The n-player equilibrium w/ 2 independent species*

Assume there are *n* symmetric countries competing for harvest of 2 biologically independent species.[5] Each country maximises the following profit function subject to the steady state of logistic growth of the stocks. The interdependency among fishermen is reflected in the equilibrium of growth functions:

$$\max_{E_i} p_1 q E_i x_1 + p_2 q E_i x_2 - cE_i \text{ , } i=\{1,2,\ldots,n\} \tag{11}$$

5 The model can straight forward be extended to *m* species, but we stay with two species for later comparison to the biologically dependent species.

$$\text{s.t. } x_j = \frac{K_j}{R_j}(R_j - q\sum_{i=1}^{n} E_i), j=\{1,2\}.$$

From the FOC the reaction functions for each country can be derived:

$$E_i = E^* - \sum_{k \neq i} \frac{E_k}{2} \quad i=\{1,2,\ldots,n\},\ k=\{1,2,\ldots,n\}. \tag{12}$$

Since we know countries are symmetric we can easily solve for the optimal effort level by each country:

$$E_i = \frac{2}{n+1} E^*, \tag{13}$$

and the total optimal effort in a Nash equilibrium becomes $E_T = \frac{2n}{n+1} E^*$ and with n approaching infinity the total fishing effort approaching restricted open access effort $2E^*$.

The equilibrium stocks are:

$$x_j = K_j - \frac{K_j q \frac{2n}{n+1} E^*}{R_j}, \quad j=\{1,2\}. \tag{14}$$

From this it is seen that stocks might be eliminated if the total effort is too high. Since total effort depends on the number of non-cooperative exploiters we can find the critical number of players playing a Nash game, which just shifts from preserving the biodiversity to eliminating one species. Equalling equation (14) to zero for each of the species we find this critical number of players, but starting by minimising the bio-technical productivity (R_j/q for species $j=\{1,2\}$) we can simplify the problem and only consider the number of players for the species with the lowest biotechnical productivity (Clark 1990). In our model, where there is no selectivity, illustrated by the same catchability for all species, it is therefore sufficient to find the species with the lowest intrinsic growth rate. In addition Clark (1990) shows that this species will only be eliminated if the cost-price ratio for other species in question is sufficiently low. Thus for elimination of one species to occur, we need to find the stock with the lowest biotechnical productivity, call that stock l. This stock will only face elimination if the following condition is satisfied:[6]

$$\frac{c}{p_{j\neq l}q} < K_l \frac{1-R_{j\neq l}}{R_l} \text{ for } j,l=\{1,2\}. \tag{15}$$

If for example stock 1 has the lowest biotechnical productivity ($R_1/q < R_2/q$) then stock one would face elimination if $\frac{c}{p_2 q} < K_1 \frac{1-R_2}{R_1}$.

Only if the above equation is satisfied will one of the stocks be extinct. Thus, equation (15) is a necessary condition for extinction to occur. If equation (15) is not satisfied there is no critical limit on the number of players exploiting the two stocks in the aspect of preserving the ecosystem, and it must be assumed that this will result in a restricted open access exploitation of the stocks. If equation (15) is satisfied, then the critical number of players defined by equation (14) equal to zero. If equation (15) is satisfied, then extinction will occur for the stock with lowest biotechnical productivity when the number of non-cooperative exploiters reaches:

$$n^* = \frac{R_l}{2qE^* - R_l}, \tag{16}$$

where l is the stock with lowest bio-technical productivity.

n^* is now defined as the limit of non-cooperative exploiters where we will shift from preserving to non-preserving biodiversity. For a number of players ex-

6 This is simply a rewritten version of Clarks two- condition for a species to be extinct (Clark 1990, p. 315).

ceeding n^* not all species in the ecosystem will be sustained, e.g. equation (15) is satisfied such that the species with lowest biotechnical productivity will be extinct . Seemingly, the independency of the stocks implies that it is sufficient to consider the single species independently with regard to the critical number. There is, however, implicitly economic interdependence among the species because of the lack of selectivity. This interdependency is reflected in the optimal effort level being dependent on all intrinsic growth rates and carrying capacities for all species in the multispecies fishery. Thus the optimal effort level E^* is dependent of the carrying capacity and the intrinsic growth rate of all the species in this multispecies fishery.

We now proceeds towards finding analytical characteristics of n^* for biological dependent species.

4. Multiple biological dependent stocks

4.1. Two biological dependent stocks

In many fisheries there is not only an economic interdependence between stocks but also a biological interdependency among stocks. Biological interdependency may have different stature; It may be predator-prey relationship as, such as the seals feeding on smaller pelagic fish, it may be a prey-prey relationship e.g. the cod feeding on sprat and the sprat feeding on cod eggs in the Baltic Sea or it may be symbiosis or mutualism which has a particular importance in tropical reef environment, such as cleaner fish and their mutualism with other species.

We consider a static game between n agents harvesting common natural resources (see also Mesterton-Gibbons 2000). Assume equilibrium use of the two fish stocks by symmetric countries:

$$\frac{dx_1}{dt} = F(x_1, x_2) - \sum_{i=1}^{n} qE_i x_1 = 0 \tag{17a}$$

$$\frac{dx_2}{dt} = G(x_1, x_2) - \sum_{i=1}^{n} qE_i x_2 = 0 \,. \tag{17b}$$

The growth functions include interaction between species and are explicitly formulated as a variation of the competition model originally suggested by Gause (see Clark 1990). These growth functions can be regarded as variations of the traditional logistic growth functions:

$$F(x_1, x_2) = R_1 x_1 (1 - x_1 / K_1) - \theta_1 x_1 x_2 \tag{18a}$$

$$G(x_1, x_2) = R_2 x_2 (1 - x_2 / K_2) - \theta_2 x_1 x_2 \,. \tag{18b}$$

The parameters θi i={1,2} are referred to as the interdependency parameter between species and can be positive or negative constants. If they are both positive they describe the biological competition between the stocks, if they are both negative they describe a biological symbiosis between stocks and finally, if they have different signs they describe predator-prey relation ship, where the constant with the negative sign represent the predator. In some cases, the nature in itself is so favourable that exploitation, in this model, cannot eliminate any of the species. In other cases the nature itself will lead to elimination of one of the species. Obviously, we are only interested in the cases, where the nature itself does not eliminate a species, therefore we implicitly assume, that both stocks are positive in the natural equilibrium. If this is not true, it is not meaningful to find the critical number of players.

A main critique of the applied model in equation (18) is that the growth model applied results in a linear functional response; this means that the consumption per capita increases linearly. There exists other models for multispecies growths and consumption (see Noy-Meir 1975 for a description of some of these models), but they lack the modelling advantages of the one we suggest. A variation of this type of model is also applied in Hannesson (1983) and in the theoretical paper by Mesterton-Gibbon (1988).

It follows from the above model that the following two equations jointly describes the equilibrium fish stocks when n players exploit the stocks, where $E_T = \sum_{i=1}^{n} E_i$ describes the total effort by all exploiters:

$$x_1 = \frac{K_1}{R_1}(R_1 - qE_T - \theta_1 x_2) \tag{19a}$$

$$x_2 = \frac{K_2}{R_2}(R_2 - qE_T - \theta_2 x_1). \tag{19b}$$

Inserting equation (19b) in equation (19a) and solving for x_1 yields equilibrium stock species 1. Inserting this equilibrium stock for species 1 in equation (19b) yields the equilibrium stock for species 2. The two equilibrium of the stocks depending on applied effort are defined as:

$$x_1 = \frac{K_1(-R_1R_2 + K_2R_2\theta_1 + E_Tq(R_2 - K_2\theta_1))}{-R_1R_2 + K_1K_2\theta_1\theta_2} \tag{20a}$$

$$x_2 = \frac{K_2(-R_1R_2 + K_1R_1\theta_2 + E_Tq(R_1 - K_1\theta_2))}{-R_1R_2 + K_1K_2\theta_1\theta_2}. \tag{20b}$$

We see from equation (20a) and (20b) that we can no longer, as the case with biological independent species, be certain that an increase in the total effort level reduces the equilibrium stocks. Whether an increase in total effort increases or decreases the equilibrium stocks depends how the biological parameters are in relation to each other. The following exemplifies this for species 1:[7]

- If $Sign[R_2 - K_2\theta_1] \neq Sign[-R_1R_2 + K_1K_2\theta_1\theta_2]$, which is always the case in a predator-prey model, where species 1 is the predator, but could also occur for competition and mutualism, then we have a case, where the equilibrium biomass of species 1 diminish with an increase in effort.

7 One can reach the same conclusions for species 2, simply by switching the subscripts 1 and 2.

- If on the other hand $Sign[R_2 - K_2\theta_1] = Sign[-R_1R_2 + K_1K_2\theta_1\theta_2]$, which could be a predator-prey case, where species 1 is the prey, or in a competition or mutualism model, we have a case, where the equilibrium biomass for species 1 increases with the effort. This means that the fishing pressure has less impact on the species compared to the ecological pressure due to the biological interdependency.

We can conclude that with biological interdependence among species an effort increase in the fishery is by itself not sufficient to say whether the equilibrium stock will increase or decrease since the ecological pressure from the interdependence also has an effect.

4.2. Two biological dependent stocks w/ sole owner

The sole owner optimum effort with interacting species is defined by the equilibrium yields (equations 19a+b) and then maximising the economic benefits from a single effort level (equation 11 with new steady state conditions). The solution to the problem yields:

$$E^* = \frac{c(-R_1R_2 + K_1K_2\theta_1\theta_2) + q(K_2p_2R_1R_2 + K_1(p_1R_1R_2 - K_2p_1R_2\theta_1 - K_2p_2R_1\theta_2))}{2q^2(K_1p_1R_2 + K_2(-K_1p_1\theta_1 + p_2(R_1 - K_1\theta_2)))}. \qquad (21)$$

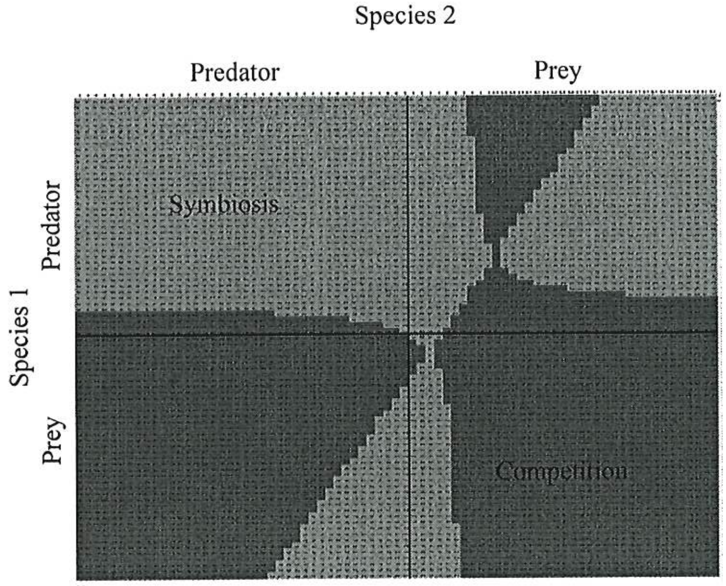
This solution corresponds to the solution in equation (7) if $\theta_1=\theta_2=0$. Whether the optimal effort in a dependent two-species setting is higher or lower than the baseline in (7) depends on the sign of the interdependency.

For illustrative purposes we have set up a numerical example comparing the effort level when species are independent and dependent, respectively. This corresponds to comparing equation (7) and equation (21). For the illustrative purpose following parameter values are applied:

Table 1. Parameter values applied for simulation

p_1	p_2	R_{low}	R_{high}	$K_1 = K_2$	c	q	θ_1	θ_2
1	2	0.3	0.9	50	7	0.5	[-0.2;0.2]	[-0.2;0.2]

Figure 1. Comparison on optimal effort level for dependent and independent species



Note:
Optimal effort when species are dependent is larger
Optimal effort when species are independent is larger

From figure 1 we notice that the optimal effort in the case of a competition (predator, predator) among species will be larger when species are dependent than when they are independent. This is caused by the harvest taking some of the pressure away from the species, this pressure does not occur when species are independent. When there is a mutualism among species, then the optimal effort will be larger when species are independent and the mutualism does not exist compared to the case when species are dependent. In the case of predator-prey it is harder to say which optimal effort level is the largest. In these cases it depends on the relative price and the growth of the two species. In the lower left corner we have the largest optimal effort when species are independent. This is the case when the species with the lowest price and the lowest case also is a prey, this is intuitively clear from the fact that the 'prey-pressure' is not available in the independent case, and therefore the optimal effort can be higher in this case.

4.3. Two biological dependent stocks w/ n players

With n symmetric players the problem is similar to the case with independent species and we have $E_i = \frac{2}{n+1}E^*$ and the total effort level employed in the industry in a Nash equilibrium is as in the case with biological independent stocks $E_T = \sum_{i=1}^{n} E_i = \frac{2n}{n+1}E^*$.

The steady state stocks in Nash equilibrium are defined by the following equations:

$$x_1 = \frac{K_1\left(-R_1R_2 + K_2R_2\theta_1 + \frac{2n}{n+1}E^* q\left(R_2 - K_2\theta_1\right)\right)}{-R_1R_2 + K_1K_2\theta_1\theta_2} \quad (22a)$$

$$x_2 = \frac{K_2\left(-R_1R_2 + K_1R_1\theta_2 + \frac{2n}{n+1}E^* q\left(R_1 - K_1\theta_2\right)\right)}{-R_1R_2 + K_1K_2\theta_1\theta_2}. \quad (22b)$$

The critical number of players where one of the stocks is eliminated is defined by setting equation (22a) or (22b) equal to zero and solve for n. It is, however, not always the case, that there exist such a critical number of players that will eliminate one of the stocks. Since solving this might result in negative n or in n's where the stock would actually benefit from more players – the 'comedy of the commons'. The critical number of number of players, which is the knife edge for eliminating or no eliminating one species, exist if under open access one of the species is eliminated, and if a natural equilibrium exists. If a critical number of players exist it is derived according to the following formula for each stock:

$$n_j = \frac{R_j R_w - K_w R_w \theta_j}{2qE^* R_W - R_j R_w - 2E^* K_w q^* \theta_j + K_w R_w \theta_j}, j,w=\{1,2\},\ w \neq j. \tag{23}$$

Define $n_{\min} = \min_j n_j$ and $n_{\max} = \max_j n_j$ and let n^* be the critical number of non-cooperative players exploiting two biological dependent species that will no longer be able to sustain the ecosystem. n^* is then the variable we are seeking. The question is whether a stable or an unstable equilibrium of harvesting the stocks exists. If the equilibrium is stable for a single stock j, then an increment in the number of players compared to n_j, will decrease the stock size for stock j. On the other hand, if this is not true for one or more of the stocks then the stability of the equilibrium is more complicated.

To understand the logic intuition behind stocks growing with the pressure from fishery, and thus a higher critical number of players, one needs to remember the multispecies setting. Imagine species 1 being a prey, it faces a large biological pressure from species 2 (for our model this occurs when θ_1 is very large and/or the biomass of stock 2 is very large). A non-selective harvest takes out harvest from both species, but the reduction in the stock 2 reduces the pressure on stock 1 and this pressure reduction is numerically larger than the pressure from the exploiters. Mathematically this will occur when:

$$\left| q\sum_{i=1}^{n} E_i \right| < \left| \theta_j x_w \right| \text{ for } \theta_j > 0. \tag{24}$$

When inequality (24) is satisfied the 'Tragedy of the Commons' does no longer occur, we are instead facing a 'Comedy of the Commons'.

Based on the stability issue, several conditions are needed to define n^*. These conditions correspond to equation (15) but are fare more complicated due to the biological interdependence. The conditions are:

1. If $n_{\min} < 0$ and $x_1(n_{\min}) > x_1(n_{\max})$ and $x_2(n_{\min}) > x_2(n_{\max})$ then $n^* = 0$.

A natural biological equilibrium with positive stocks does not exists, since at $n^*=0$ one of the stocks mathematically is negative, which is interpreted as an elimination of that stock.

2. If $n_{\min} \geq 0$ and $x_1(n_{\min}) > x_1(n_{\max})$ and $x_2(n_{\min}) > x_2(n_{\max})$ then $n^* = n_{\min}$.
   This is a traditional case, where a natural equilibrium exists and more players result in lower stocks for both species. n^* represents a stable equilibrium and determines the number of players that exactly extinct one of the stocks.

The following two conditions apply for both $n_{\min} \geq 0$ or $n_{\min} < 0$:

3. If $x_1(n_{\min}) < x_1(n_{\max})$ and $x_2(n_{\min}) < x_2(n_{\max})$ then n^*=restricted open access or 0.
   The stocks will, due to their biological conditions, grow with the pressure from fishery. The players will be attracted to the fishery[8] until we end with restricted open access equilibrium. At the restricted open access equilibrium, it should be tested whether both stocks are positive. If not, no one can exploit the stocks in a profitable way and the critical number of players is zero.
4. If $x_j(n_{\min}) < x_j(n_{\max})$ and $x_w(n_{\min}) > x_w(n_{\max})$ $w \neq j$:
   One stock (j) grows with the pressure from the fishery while the other stock (w) is reduceed with the pressure form the fishery.

   a. If $n_{\min} = n_w > 0$ then $n^*=n_{\min}$:
      The stock w is at zero for $n_{\min}$ and an increase in the critical number then stock w will be eliminated, therefore $n^*=n_{\min}$. The derived critical value results in a stable steady state.
   b. If $n_{\min} = n_w < 0$ then $n^*=0$:
      The stock w is at zero for $n_{\min}$ and an increment in n would eliminate stock w. Since the critical number is negative this means no one at all can exploit the stock, thus no natural equilibrium exists.

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8 This implicitly assumes a positive profit is possible for a sole owner.

c. If $n_{\min} = n_j$ then $n^*=n_{\max}$ or 0:

Stock j is zero for $n_{\min}$, but this stock gain from the fishing pressure, therefore $n^*=n_{\max}$ if $n_{\max} \geq 0$. The original derived equilibrium ($n_{\min}$) is an unstable steady state, but stability will be accessed at a higher level of players ($n_{\max}$). If $n_{\max} < 0$ then $n^*=0$ since the natural equilibrium does not exist.

The biological interdependency of the species creates more complexity when determining sustainability of the ecosystem for the species. An additional dimension is added as the tragedy of the commons does not always occur. The bio-technical productivity is no longer in itself sufficient to consider for finding the critical number. Equation (23) including condition 1-4 is an extension of equations (15) and (16) since it also includes the interrelations between the species. If the interrelations are zero ($\theta_j=0$), equations (15) and (16) are in themselves sufficient.

The critical number in equation (23) depends on several economic parameters through the optimal baseline effort (E^*). Appendix A analyses the effects on how this optimal baseline effort changes when economic parameters are changed and how the critical number of players changes if optimal effort level is changed. Based on this analysis it is difficult to say anything concrete on what happens to the critical number unless since it depends highly on balance between the prices, intrinsic growths, the carrying capacities and the interdependency among species.

5. Simulations

To get a better understanding of the analytical results in section 4, and to elaborate particular on the case with biological dependency we simulate exploitation of two stocks with biological dependency. We define two stocks with identical carrying capacity, the intrinsic growth rate of the two stocks can be high or low, one stock has a higher economic price than the other. This gives four cases to consider:

Case 1: Both stocks having low intrinsic growth rate.
Case 2: Both stocks having a high intrinsic growth rate.
Case 3: Low valued stock has a low intrinsic growth rate, high value stock has a high intrinsic growth rate.
Case 4: Low valued stock has a high intrinsic growth rate, high value stock has a low intrinsic growth rate.

Within each case we allow for predator-prey, competition and mutualism, as we let the interdependency parameter (θ) vary between positive and negative for both species.

We simulate the natural equilibrium and the critical number of non-cooperative players where extinction of one species occur for different biological dependence. The biological interdependence is varied in model, and results will be represented for all combinations of dependency in the range. The applied parameters are represented in table 2.

Table 2. Parameter values applied for simulation

p_1	p_2	R_{low}	R_{high}	$K_1 = K_2$	c	q	OA	MS	θ_1	θ_2
1	2	0.3	0.9	50	7	0.5	60	60	[-0.2;0.2]	[-0.2;0.2]

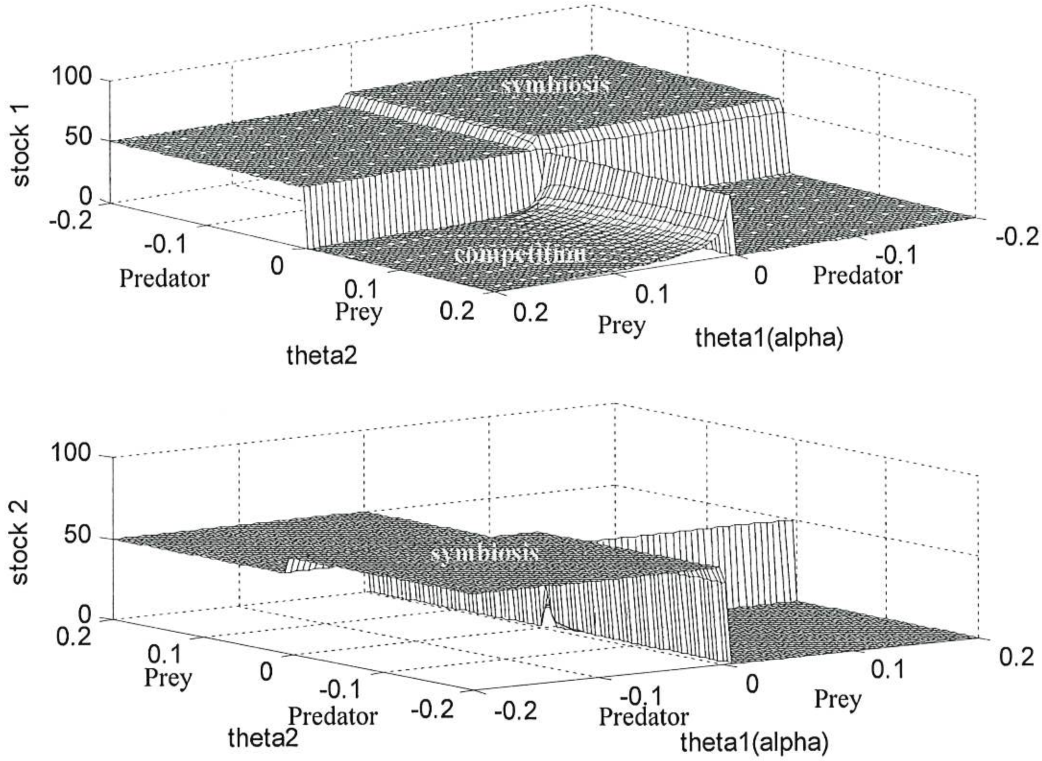
We have defined an upper limit of players which we refer to as restricted open access (OA) and an upper limit for the stock, a maximum stock size (MS). This is purely for illustrative purposes since some conditions are so favourable that we have a case of the comedy of the commons or a case with symbiosis, where stocks will jointly grow unlimited.

5.1. Natural equilibria

We start out by simulating the natural equilibria for different interdependency among species, to identify where the two species can coexist. If the species cannot coexist, we do not have a natural equilibria and it is not relevant to search for a places where one species is extinct. We are simulating the natural equilibria for all the different cases.[9] Figure 2.a illustrates the patterns for natural equilibrium for both species with a low intrinsic growth rate (case 1) as function of interdependency among species. Appendix B includes the natural equilibria for other cases.

9 The stocks are symmetric, therefore (low, high) is equivalent to (high, low) for the natural equilibria. The later model includes economic parameters, and since the species a valued differently and (low, high) and (high, low) are no longer equivalent.

Figure 2.a. The natural equilibria for two stocks both with a low intrinsic growth rate (case 1)



All figures for the natural equilibria (figure 2.a and figures B.1 and B.2 in appendix B) look very much alike. In the symbiotic case (θ_1, θ_2<0) both stocks are above their carrying capacities since they both benefit from other species existence. These upper plateaus when there is a symbiosis (or mutualism) among species are higher than the carrying capacities due to the upper limit for maximum stock size (MS), which we forced into being slightly higher than the carrying capacity. The theoretical model itself, suggests that the stock could jointly grow to very high stock levels.[10] In the case of predator-prey situations (θ_j>0 (prey), θ_w<0 (predator)), the dominant cases in the figures are the cases in which one of the stocks becomes extinct. However, there is a narrow parameter space at the positive θ-parameter (the prey) close to zero, where both species

10 The reason for this is the linearly increase in the per capita consumption (mutualism) with the multispecies, which is also mentioned in connection with equation (18).

can coexist. Finally, the case of competition (θ_1, θ_2>0) is described by decreasing stock levels e.g. species 1 decreased with increasing θ_1 and species 2 decreases with increasing θ_2. Our conclusion based on these simulation results are that the general pattern for the coexistence of species does not change with the change in intrinsic growth, what changes is the magnitude of the contours.

5.2. Species preservation and number of non-cooperative exploiters

This section illustrates the results of the simulation model. The results are presented as three-dimensional figures that describe the critical numbers of players in a non-cooperative exploitation of two stocks where one of the stocks is eliminated (n^*) on one axis and the two interdependence parameters (θ_1 and θ_2) on the other two axes. In the cases, where the natural equilibrium itself eliminates one of the stocks, the number of players is zero. The number of players is derived based on equation (29) and on the conditions 1-4, and is illustrated for a range of interaction (competition, predator-prey and symbiosis) among the two species. Again, it is important to realise, that we have set an upper limit of 60 players which in our simulation represents a restricted open access.[11] It is not the case, that the restricted open access equilibrium crashes the ecosystem, it is merely assumed that in a rational static bio-economic model, there is no reason to look for players above the restricted open access.

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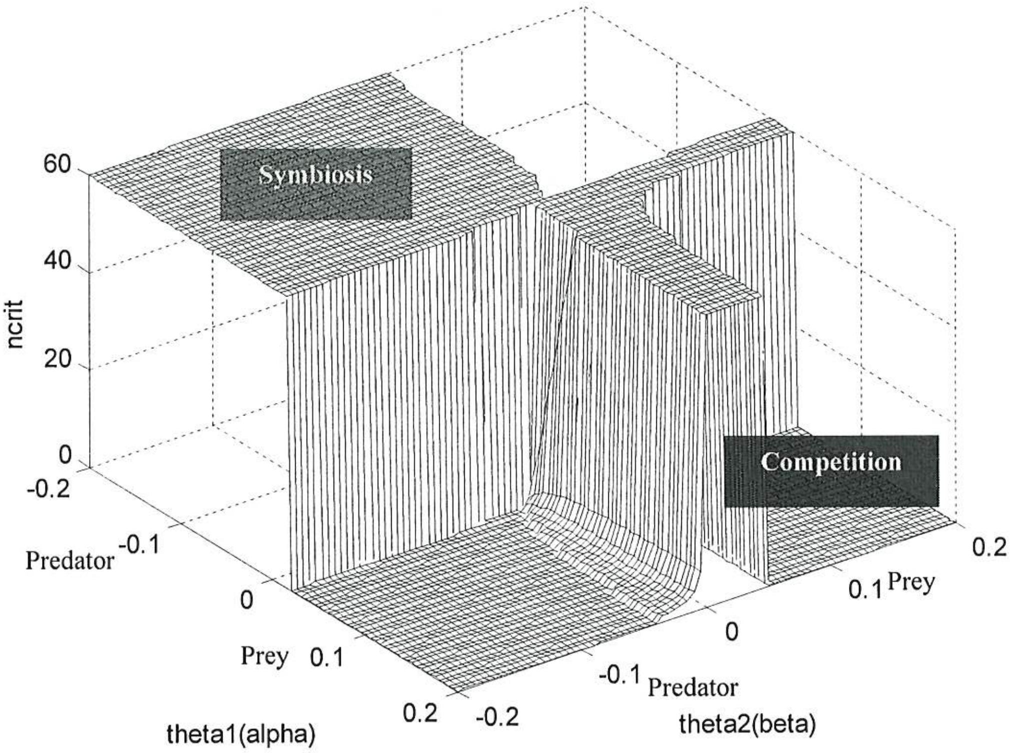
11 We have for illustration purposes set this limit, otherwise, the scale on the ncrit axis would be too large to present anything meaningful.

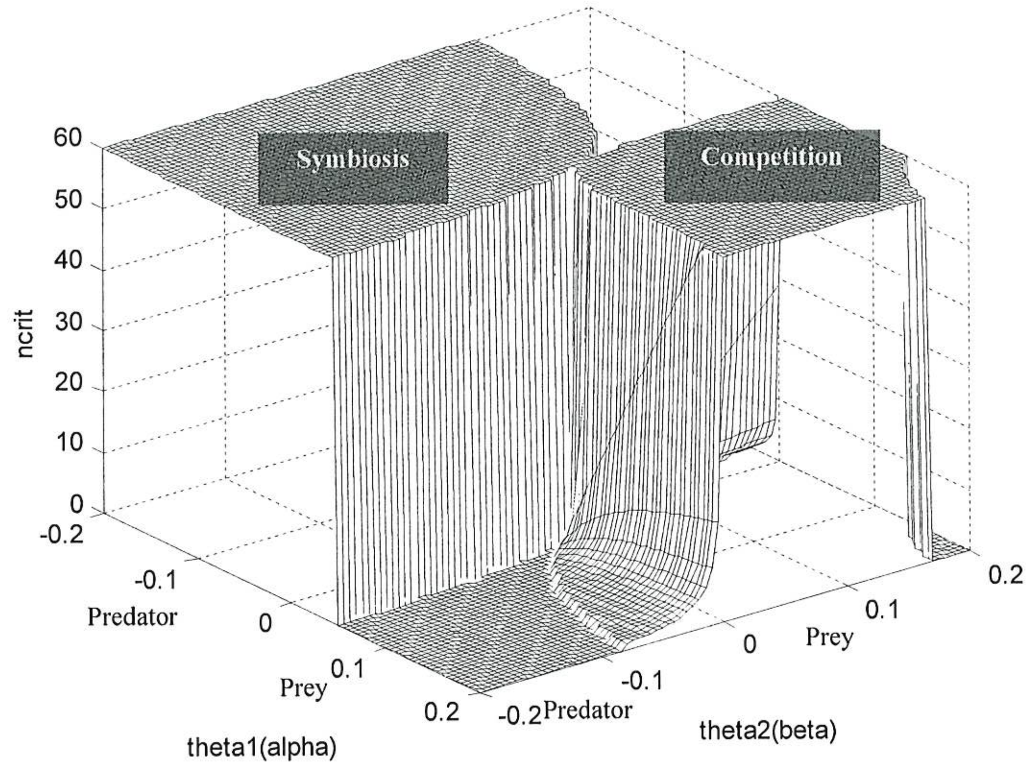
Figure 3.a. Critical number of players, where the ecosystem cannot be sustained (case 1)



Note: ncrit is identical to n* in the theoretical model.

The upper plateaus in figure 3.a and also in the figures 3.b-3.d represent the restricted open access equilibrium, where both species will coexist with the high number of non-cooperative exploiters. For all cases the symbiosis always leads to an upper plateau. Figure 3.a shows that there are only limited areas, where extinction of species will occur due to the number of players. These areas are concentrated in the predator-prey models, and correspond to the areas between the upper (restricted open access) plateaus and the lower (no natural equilibria) plateaus. For a symbiosis among species, it is not surprising that, if eco-system can sustain interaction if species are independent, then a symbiosis can also sustain a restricted open access. In the case of competition among species, the ecosystem can to some extent sustain a restricted open access but if the competition becomes too large then the ecosystem will crash even without exploitation.

Figure 3.b. Critical number of players, where the ecosystem cannot be sustained (case 2)

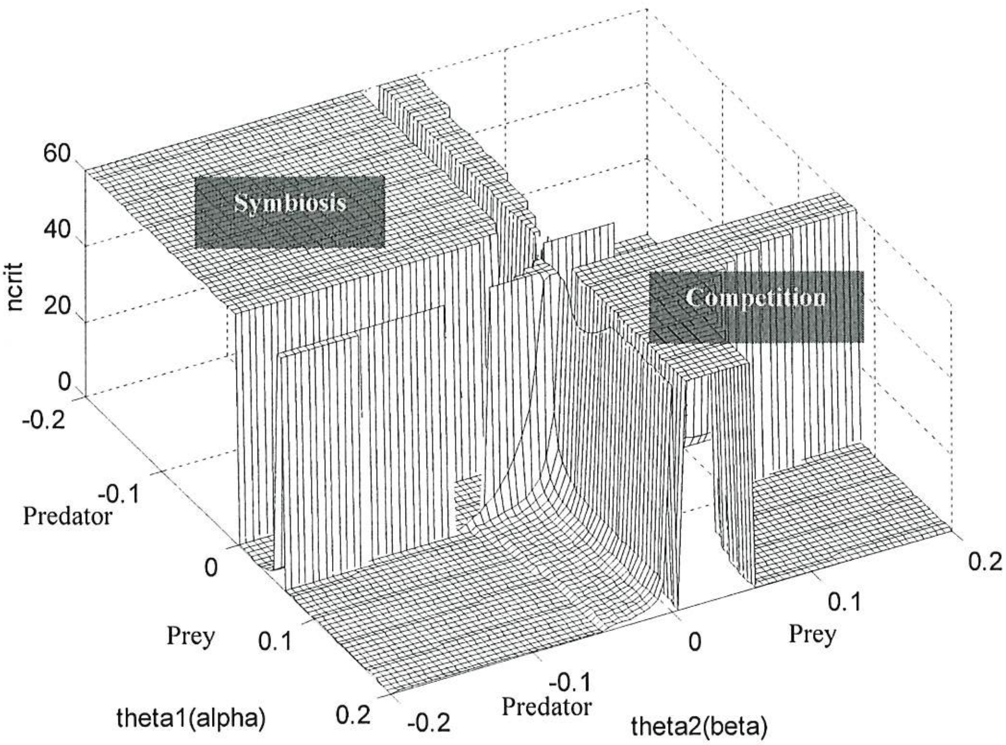


Note: ncrit is identical to n^* in the theoretical model.

In figure 3.b, where both stocks have a high growth, the overall conclusions are more or less the same as the conclusions from figure 3.a. The are, however, two main differences between them; first; the case with higher intrinsic growth (figure 3.b) can, in the competition case, better sustain the restricted open access situation (the size of the upper plateau in the competition area is larger) and second; in predator-prey case higher predation by the high-valued species can sustain more players in the equilibrium (the rainbow coloured area is prolonged into the predator-prey square).

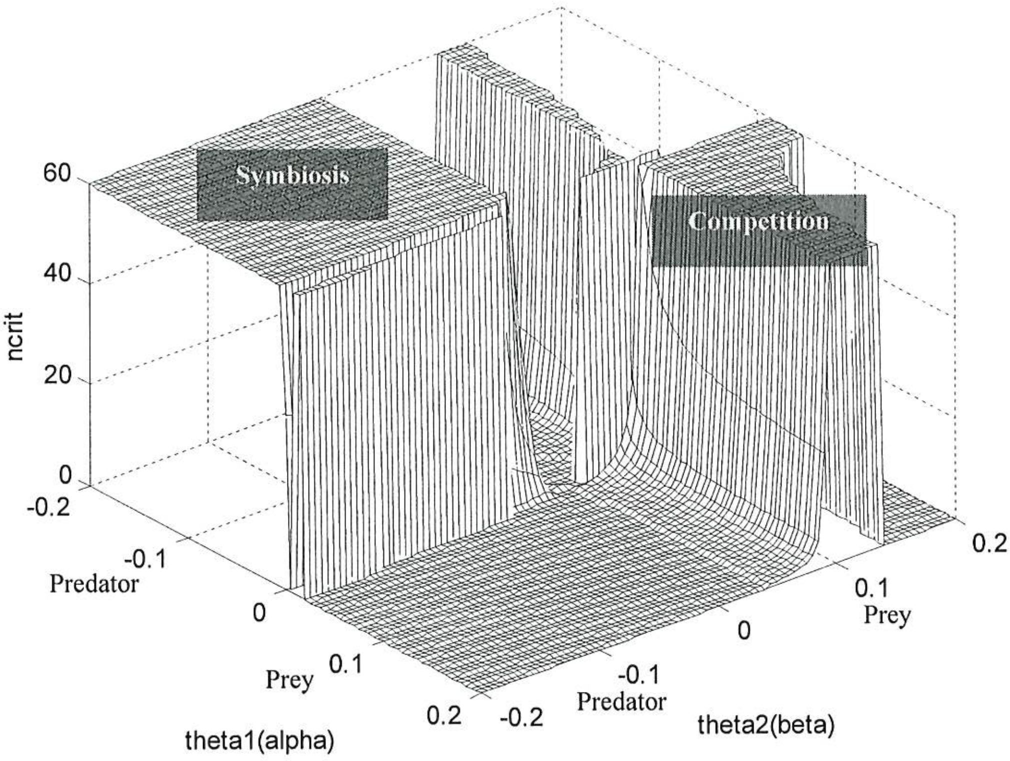
The following two figures (figure 3.c and 3.d) compare the cases with different growth rates and different price for the two stocks (case 2 and case 4).

Figure 3.c. Critical number of players, where the ecosystem cannot be sustained (case 3)



Note: ncrit is identical to n^* in the theoretical model.

Figure 3.d. Critical number of players, where the ecosystem cannot be sustained (case 4)



Note: ncrit is identical to n^* in the theoretical model.

The cases in figure 3.c and 3.d are fairly complicated with plateaus, peaks and canyons appearing in many places. This shows that small changes in the ecosystem parameters can have a significant economic effect: a system previously able to sustain several fishers may suddenly be able to sustain only a few fishers or none at all. It is, however, still the case that the symbiotic interaction can sustain even restricted open access and the same is true for some parameters in the competition square.

6. Discussion and Conclusion

The paper merges the bio-economic multispecies modelling with the non-cooperative game theory. Thereby an analytical framework for defining the behaviour for non-cooperative exploiters harvesting biological dependent and independent multispecies in a non-selective manner is set up. In this setup we have analytically defined the conditions for species preservation when non-cooperative exploiters harvest in the multi-species fisheries, with is a contribution to the literature for multispecies, where the bio-technical productivity is not sufficient. In this context, it is important to notice that we set up a simple non-spatial model, and in a spatial setting, like the natural environment, the different patches are likely to have different characteristics' and therefore different species may survive in different patches.

When species are biological independent it is sufficient to consider the bio-technical productivity to find the stock which is in danger of not being preserved. When species are biological dependent it is not straight forward to apply the biotechnical productivity from the independent model. The conditions, for which the stock is in danger of not being preserved, are far more complicated and requires also including the interdependency parameters. We contribute to the literature with a general definition of the critical number of non-cooperative players to preserve biodiversity in a multispecies fishery for all possible set of interdependency parameters.

We have in our analytical model with biological dependent species shown that the 'Tragedy of the Commons' does not apply for some parameters, but instead we have the 'Comedy of the Commons' where restricted open access is favourable.

Applying the results from the analytical model, we simulated a multi-species fishery with two dependent species. We experienced that the natural equilibrium looks more or less the same for different intrinsic growth rates. We also found the obvious result that if independent stocks can sustain a restricted open access then a symbiotic relationship between species can also sustain restricted open access.

Among other lessons to be learned from the simulations are that it is primarily the low values of interdependency parameters with are the interesting values, but in that parameter range the model is very sensitive to small changes in those small dependency values. A small change in the interdependency can lead to big changes in the critical number of non-cooperative players.

Finally, the when there is competition among species a higher intrinsic growth rate tend to extend the range of parameters for which restricted open access is sustained.

Among areas for further research are simulations of cases where a two-species fishery with biological independent stocks has a limited number of players which can preserve the biodiversity. It is expected, that such a simulation example could give more information about the critical number function for small values of dependency.

The biological independent case is straight forward to extend to more than two species, but the biological dependent species requires more considerations for the interactions for the species. We believe that it is a possible research issue, but it would require a researcher with a lot of courage.

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Appendix A. Sensitivity analysis when changing economic parameters

Section 4.3 investigates the conditions for the number of non-cooperative players that can preserve the two species in the eco-system. This appendix conducts a sensitivity analysis on the baseline optimal effort when changes in the economic parameters occur. Further the impact on the baseline effort on the number of players is analysed. Together this results in a sensitivity analysis on the critical number of players when economic parameters are changed.

Optimal effort and price of species

If the price of species increases, then the change in the optimal baseline effort, and thereby also effort for non-cooperative players, will look like:

$$\frac{\partial E^*}{\partial p_1} = \frac{K_1\left(cR_2 + K_2\left(p_2 q\left(R_1 - R_2\right) - c\theta_1\right)\right)\left(R_1 R_2 - K_1 K_2 \theta_1 \theta_2\right)}{2q^2\left(K_1 p_1 R_2 + K_2\left(-K_1 p_1 \theta_1 + p_2\left(R_1 - K_1 \theta_2\right)\right)\right)^2} \tag{25a}$$

$$\frac{\partial E^*}{\partial p_2} = \frac{K_1\left(cR_1 + K_1\left(p_1 q\left(R_2 - R_1\right) - c\theta_2\right)\right)\left(R_1 R_2 - K_1 K_2 \theta_1 \theta_2\right)}{2q^2\left(K_2 p_2 R_1 + K_1\left(-K_2 p_2 \theta_2 + p_1\left(R_2 - K_2 \theta_1\right)\right)\right)^2} \tag{25b}$$

To find the effects on the optimal effort level in the case of an increase in the price of one species it is necessary to figure out whether (25a) and (25b) are positive or negative.

It is clear that the denominator, $2q^2\left(K_2 p_2 R_1 + K_1\left(-K_2 p_2 \theta_2 + p_1\left(R_2 - K_2 \theta_1\right)\right)\right)^2$, will always be positive because of the second power, the nominator, $K_1\left(cR_2 + K_2\left(p_2 q\left(R_1 - R_2\right) - c\theta_1\right)\right)\left(R_1 R_2 - K_1 K_2 \theta_1 \theta_2\right)$, is, however more ambiguous. The following focuses on the sign of the nominator:

If $Sign\left[cR_2 + K_2\left(p_2 q\left(R_1 - R_2\right) - c\theta_1\right)\right] = Sign\left[R_1 R_2 - K_1 K_2 \theta_1 \theta_2\right]$ then an increase in price increases effort.

In the case of a predator-prey model θ_1 and θ_2 will have different signs and therefore the last term will be positive.

A sufficient but not necessary assumption for the effort to increase as a result of a price change for one of the species is then that the growth of the species, which experience the price change, is larger than the growth of the other species. For a price change for species 1, this will look like $R_1 > R_2$ and that $p_2 q(R_1 - R_2) \geq c\theta_1$. This is more likely to be true if the intrinsic growth of species 1 is relative high to species 2 and if species one is the predator (θ_1<0). It is thus seen that for the effort to increase, it is a balance between the value of the two species, their intrinsic growths and their interdependency.

Optimal effort and cost of harvesting

If the cost of harvesting is changed, then the effort is changed according to following:

$$\frac{\partial E^*}{\partial c} = \frac{-R_1 R_2 + K_1 K_2 \theta_1 \theta_2}{2q^2 \left(K_1 p_1 R_2 + K_2 \left(-K_1 p_1 \theta_1 + p_2 \left(R_1 - K_1 \theta_2\right)\right)\right)} \tag{26}$$

One would expect this to be negative, such that the effort is decreased if the cost of harvesting is increased, ceteris paribus. But for this to be true either $R_1 R_2 > K_1 K_2 \theta_1 \theta_2$ or $K_1 p_1 R_2 < K_2(-K_1 p_1 \theta_1 + p_2(R_1 - K_1 \theta_2))$.

Conclusion on changes in effort, when economic parameters are changed

It is difficult to say anything concrete on what happens to the optimal effort level if the economic parameters changes. It is a balance between the prices, intrinsic growths, the carrying capacities and the interdependency among species. It can, however, be concluded, that economic parameters will, except in rare cases, change the optimal effort for the sole owner and thereby also for the *n*-players.

Critical number of players and effort level

We know from above analysis that changes in economic parameters make E^* change, and this is true without changing other parameters in the critical number of players. Changes in optimal effort can therefore be interpreted as an effect of economic parameter changes.

If the optimal effort level in the sole owner case increases, then the number of players to sustain the bio-diversity is changes according to the following:

$$\frac{\partial n^*}{\partial E^*}=\frac{2q(R_2-K_2\theta_1)(-R_1R_2+K_2R_2\theta_1)}{(-R_1R_2+2E^*q(R_2-K_2\theta_1)+K_2R_2\theta_2)^2} \text{ (Species 1)} \tag{27a}$$

$$\frac{\partial n^*}{\partial E^*}=\frac{2q(R_1-K_1\theta_2)(-R_1R_2+K_1R_1\theta_2)}{(-R_1R_2+2E^*q(R_1-K_1\theta_2)+K_1R_1\theta_1)^2} \text{ (Species 2)} \tag{27b}$$

The denominators in equation (27a) and (27b) are positive, but in order to discuss the sign of the nominator we divide into different subcategories of interdependency.

If θ_1, θ_2 <0: (symbiosis)

The nominators in equation (27a) and (27b) are negative and the critical number of players will decrease if the optimal effort level is increased.

If θ_1, θ_2 >0: (competition)

Then the number of players will decrease only if:

$R_2 < K_2\theta_1$ and $R_1 < K_2\theta_1$ or $R_2 > K_2\theta_1$ and $R_1 > K_2\theta_1$ if species 1 is binding for the critical number or $R_1 < K_1\theta_2$ and $R_2 < K_1\theta_2$ or $R_1 > K_1\theta_2$ and $R_2 > K_1\theta_2$ if species 2 is binding for the critical number.

This can be interpreted as the intrinsic growth rates of both species either have to be sufficiently large or sufficiently small otherwise the competition in the model will drive the stocks to extinction.

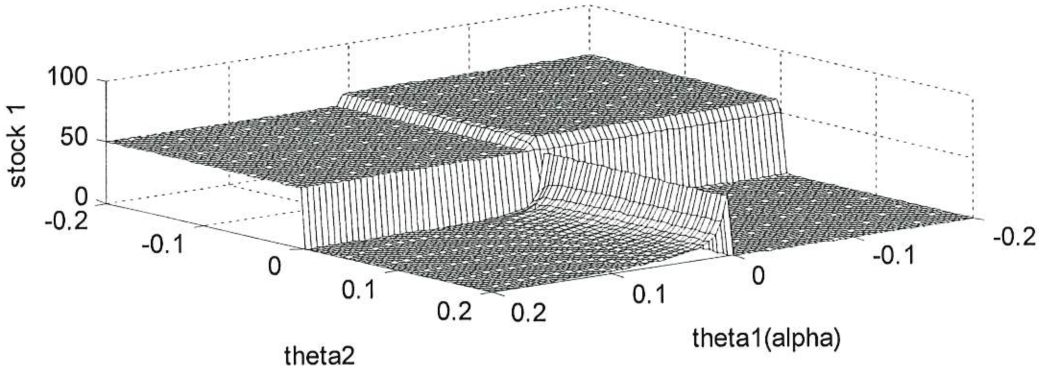
If θ_1 *<0 (predator) and* θ_2 *>0 (prey)* (or θ_2 *<0 (predator) and* θ_1 *>0 (prey)*): *(predator-prey model)*
If the predator sets the limits for the critical number of players then an increase in the optimal effort will further decrease the critical number of players.

If on the other hand the prey sets the limit for the critical number of players then this number will only decrease if $R_1 < K_1\theta_2$ and $R_2 < K_1\theta_2$ or vice versa. This means that the increase in effort is only critical if the intrinsic growths of the two species are low.

That is if the intrinsic growth rate of the prey is small then the intrinsic growth of the prey must also be small and vice versa if the number of players should increase with the optimal effort level.

Appendix B. Natural equilibria for two biological dependent stocks

Figure B.1. The natural equilibria for two stocks both with a high intrinsic growth rate (case 2)



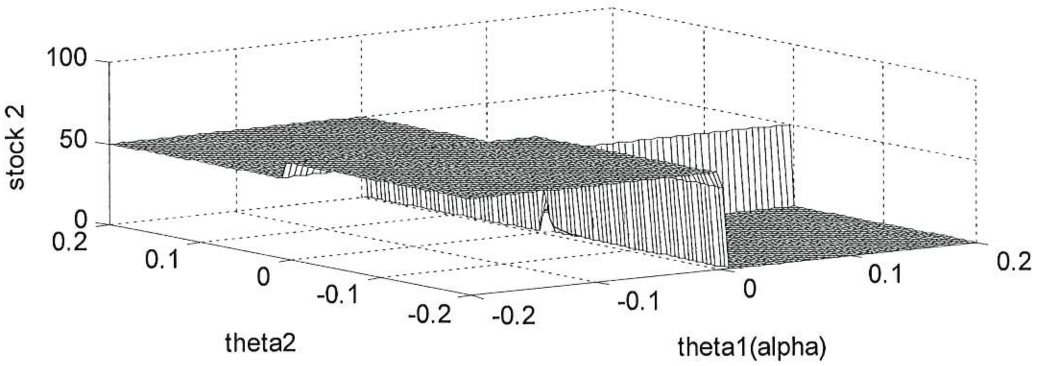
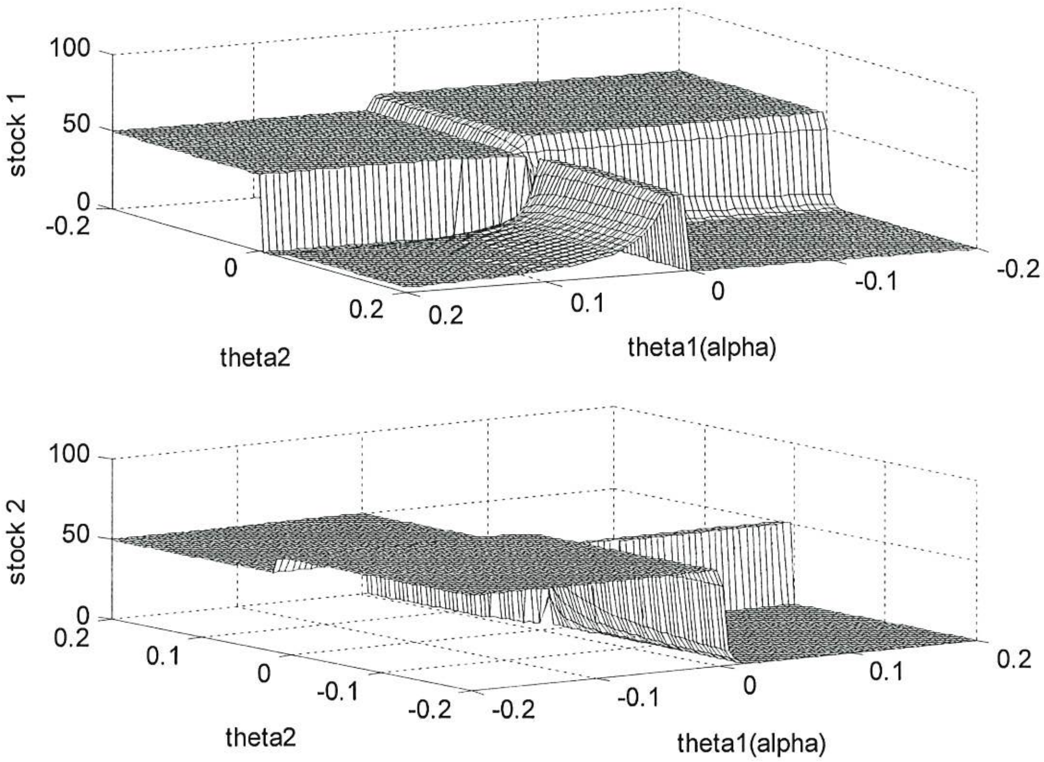


Figure B.2. The natural equilibria for two stocks both with a low and high intrinsic growth rate, respectively (case)



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