Aquaculture-fisheries interactions

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Abstract

Assuming externalities from aquaculture to fisheries, we use a Verhulst-Schaefer model of fish population-dynamics and production, coupled with an aquaculture production model, to investigate effects on open-access and rent-maximising fisheries. Externalities are modelled by letting carrying capacity, intrinsic growth rate or catchability coefficient in the fishery depend on aquaculture production. We find that the different externalities can give opposite effects on steady state fishing effort, yield and stock, even for only "negative" externalities. With the catchability externality, increased unit cost of fishing can imply reduced aquaculture production in social optimum, under reasonable assumptions. We also look at allocation between the industries under three different management regimes for coastal areas: 1) Aquaculture has a primary right of use; 2) Optimal management of aquaculture and fishery; 3) Fishers have a primary right of use, but may allow marine farming, possibly against payment.

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1 Introduction[1]

There is increasing rivalry for coastal resources (Buanes et al 2004). In some cases the rivalry is for access to the same resource, in other cases it is to avoid negative externalities from others' use of resources. Understanding how different users and uses might affect each other is obviously important, as well as how different coastal management regimes can influence this. Aquaculture and fisheries are important industries in many coastal areas, and conflicts between them are not uncommon (e.g. Dwire 1996, Grey and Sullivan 2003, Murai 1992). In this paper we consider the use and management of coastal areas, when there are external effects of aquaculture on fisheries.

Marine aquaculture has in the last 4-5 decades grown steadily, both in production volume and value. In 2000 aquaculture represented around 32% of total world fisheries landings by weight, according to FAO-statistics (Tacon 2003). Marine aquaculture made up nearly half of this production.[2] Molluscs are the largest species group in marine aquaculture, with 46% of total weight. Finfish is around 9%. Aquaculture can have many different types of environmental effects. Most of these have been known for more than 20 years (Black 2001:vi).

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[2] Including plants, 44% of marine aquaculture by weight.

We want to analyse how different types of aquaculture externalities can affect open access and sole-owner fisheries. For this purpose a very general model is developed, in order to grasp the most important qualitative effects. It can be used for a multitude of types of externalities. We consider externalities on either wild fish growth-dynamics, or on fishing operations. Effects on growth-dynamics are modelled by letting the area's carrying capacity for the fish stock, or the stock's intrinsic growth rate, depend on aquaculture production volume. Effects on fishing operations are modelled by letting the efficiency of fishing effort depend on aquaculture. As far as we know, no one has analysed aquaculture externalities on fishing effort efficiency previously. We assume that conflicts between the industries are local, and hence that no significant market interactions exist between the actors. Our model has fish population-dynamics and production based on the classic Verhulst-Schaefer fisheries model (e.g. Clark 1990; Ch.1). We consider effects on fishing effort, fish stock size, wild fish yield and rents in steady state.

While the two externalities on growth dynamics give similar results on steady state fishing effort, fish stock levels and yield, the externality on fishing effort efficiency gives the opposite effects in most cases, even if all the three externalities are "negative". Being certain about what type of externality aquaculture will have on a fishery is hence crucial for managers of an area.

We also want to see how different coastal management regimes affects the allocation of resources between the industries: (1) Areas may be practically unregulated regarding aquaculture, with marine farmers setting up their operations without regard to local fisheries, or aquaculture has positively been given a primary right of use; (2) Regulators try to achieve optimal management; (3) Fishermen may have a "historical" right to an area, and can decide

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whether, or to what extent, marine farming can be established. The last regime also includes a situation where fishers can demand compensation from marine farmers when there are negative external effects of aquaculture.

Case (3) is inspired by the situation in Japan (Murai 1992) and New Zealand (Gibbs 2003). In Japan fisheries cooperatives are actually given the right to areas, and anyone wanting to establish a marine farm must get their permission. On New Zealand new legislation from 2005 give fishers the primary right to ocean areas when (prospective) marine farmers want access. In neither cases payment for access are mentioned in legislation, but not ruled out, as far as we know. We hence investigate what is likely to take place where one group has been given a primary right to an area, but new stakeholders are pressing for access.

Previous studies considering a carrying-capacity externality from aquaculture (Hoagland et al 2003) have found some surprising comparative statics results under optimal management, and we also want to see if our model reproduces those surprising results.

The paper is organised as follows: In the section 2 we first review possible types of interactions between aquaculture and fisheries, and then previous economic analysis of such interactions; We present our model in section 3, first with a carrying capacity externality, and then the variants where the intrinsic growth rate and catchability is affected, respectively; Section 4 contains the discussion and conclusions.

2   Interactions between aquaculture and fisheries

Aquaculture comes in many forms (Naylor et al 2000, Tacon 2003): Freshwater ponds or pens, marine cages where the whole life-cycle is controlled, salmon ranching where only the

primary stages of fish life is controlled before juveniles are released to the ocean and caught when they return as adults to spawn. An important distinction is between herbivore species like mussels, which use nutrients naturally in the water, and carnivores like finfish which require feeding. Naturally, with this diversity also the effects from aquaculture on the environment, fisheries, and other stakeholders, vary a lot.

We will first give an overview of possible interactions between aquaculture on fisheries, based on general literature. We classify these into 4 major types. Afterwards we go through the economics literature of aquaculture-fisheries interactions, as many economics articles consider more than one type of interaction.

2.1   General overview of interactions

Interactions between aquaculture and fisheries may be said to be of four different classes: 1) effects through impact on the physical, chemical or ecological environment; 2) effects on costs or productivity directly; 3) interactions through related product markets; 4) aquaculture feed demand may affect demand for feed-fish and hence fishing pressure (Black 2001, Cole 2002, Milewski 2001, Naylor et al 2000, ICES 2005).

Ecological interactions can go through different paths. Aquaculture in marine environments can be said to be of two main types. The dichotomy is whether the species is fed or not. For shellfish and low trophic level fish plankton naturally in the water is their nutrient. Higher trophic level fish on the other hand needs feeding. This gives rise to different ecological effects. Impacts can be divided into the following groups: impacts on the water column, impacts on the benthic environment, litter impacts, introduction of pests with structures, build-up of predators under and around farms, displacement of fishing, genetic impacts, disease risk, transmission of parasites, influences of aquaculture of wild species on their local

abundance, and effects of toxic algal blooms (Cole 2002). Aquaculture can influence the *physical or chemical environment* in its vicinity, and this may affect fish-populations directly or indirectly, as well as positively or negatively.[3] Farmed shellfish can e.g. compete with other species for nutrients, oxygen and sunlight available in the water-body, and may hence give ecological effects (Milewski 2001). Displacement of fishing could have a positive ecological effect on fish-stocks; Restricting dredging or trawling could improve conditions for wild fish, since these activities can have negative effects on the benthic communities on the seabed. On the other hand, restrictions on dredging or trawling in one area could lead to more intensive fishing and damages to benthic communities other places. If the farmed species is naturally present locally it increases the chances of ecological interactions between farmed and wild fish. Diseases, pests and parasites may be more readily transferred. Further, genetic impacts on the local stock may occur through escapement of farmed fish which breed with the local population. According to Cole (2002) the main issues for genetic impacts are translocation, inbreeding depression, genetically-modified organisms and interbreeding with natural populations. If juvenile fish is imported to an area for farming, whether the species is new or not, there is a risk of introduction of diseases, pests and parasites. The higher density of fish in pens can also increase the opportunities for pests, disease and parasites to develop and survive.

Rather than having effects on the marine environment and fish-ecology, aquaculture activities may affect fishing operations. This could be both on costs and productivity of fishing. Aquaculture structures may e.g. displace fishing activities. In addition to fishing not being

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[3] Bjørn et al. (2005) report lab experiments where coastal cod leave from tanks with water in which "foreign" fish have been. This indicates that fishermen's claim of cod fleeing old spawning grounds after salmon-farming started in the vicinity could be correct. However, they have also observed how cod can get attracted to farming pens in the field. The possibilities of high food availability in the vicinity of pens, and that the two major subgroups of coastal cod can have different behaviour, could explain this.

possible just where the marine farm is, it is common with safety areas around the farms, where fishing is prohibited. If farms are established where fishing previously occurred, increased costs or lowered productivity of fishing seems reasonable (ICES 2002).

Yet another interaction between aquaculture and wild fish can be through the product market, and several economics papers have considerer this (see below). Such an interaction is present if both industries are producing the same or otherwise marked-related species. Special focus has been on the interaction between salmon farming and wild salmon stocks.

A special aquaculture-fisheries interaction may occur with ranching, where fish is released into the ocean for growth after initial aquacultural upbringing. If it is not possible to limit access to the fish, fishermen may harvest on the resource, constituting an externality on the ranchers.

None of the literature on these interactions, at least of what we have seen, makes attempts at quantifying the external effects into variables that readily relate to economic performance. Nor do they attempt at even setting up crude models for making such quantifications. This is of course a present shortcoming, and a future research challenge.

2.2 Economic analyses of interactions

We will now review economic analysis of aquaculture-fisheries interactions. (Anderson, 1985a) considers salmon ranching and conflicts with commercial fisheries. Salmon ranching means hatching and raising salmon to the smolt stage in ponds or raceways, releasing the juveniles to the ocean, and when the adults instinctively return to the release facility they are caught for sale and for continued breeding. The interaction he models is that salmon fishers in the ocean also catch some of the salmon, reducing the efficiency of the ranching operations.

Natural and ranched salmon compete in the same market. He considers yield, harvest effort and existence of the two activities under different management regimes and parameter settings. With salmon ranching the natural salmon stock could be exploited to extinction, something which is not deemed possible with just the natural stock. Anderson and Wilen (1986) consider the strategic behaviour of a dominant salmon rancher facing a competitive open-access fishery, and possibly also public hatcheries releasing salmon smolt. They use dynamic nonlinear programming, but the basic model shares major features with Anderson's model (1985a). Primary attention is given to strategic behaviour by the salmon rancher regulating production (smolt release), and attempting to influence fishing season length. Anderson and Wilen also find that the presence of salmon ranching increases fishing pressure, reducing natural salmon stock compared to the case without ranching. However, if the salmon rancher could influence fishing season length, he would reduce fishing effort to the point where natural salmon stocks actually would be higher than with only the open access fishery.

Anderson (1985b) analyses a market interaction between an open access fishery and aquaculture. The latter can be either a competitive industry, or just dominated by a single actor. He finds that entry of aquaculture increases the total supply of fish to the market, reduces price, and increases the stock and harvest of wild fish. Ye and Beddington (1996) build on Anderson (1985b) to analyse market interactions with dynamic models. They consider the cases where the two industries produce the same product, or only partly related products. Their conclusions are similar to Anderson's.

Asche and Tveterås (2000) discuss under which fisheries management regimes expansion of aquaculture using feed from reduction fisheries could have a negative impact on fish stocks.

They conclude that it will mainly be a problem if a fishery is open access, i.e. not managed. They further investigate whether the market for fishmeal is part of the larger market for oilmeals, since this will determine if expansion of aquaculture using fishmeal can affect fishmeal prices noticeably. They conclude that it can not, at the present volume of operations, and hence will not increase fishing pressure in reduction fisheries. Hannesson (2003) considers if aquaculture can increase the supply of fish for human consumption. He assumes that feed for farmed fish must be made with fish which otherwise could be food for natural stocks of edible fish. The effect on supply depends on the efficiency of transfer from feed fish to edible fish in aquaculture versus in the ocean. Aquaculture could threaten the natural fishery by increasing demand for feed fish too much.

Hoagland et al (2003) assumes that aquaculture operations affect an area's carrying capacity for a natural fish stock. They investigate effects of this both on an open access fishery, a fishery being optimally managed by individual quotas, and if the two industries compete in the product market. In the first two cases they show how a negative effect on carrying capacity reduces the fishing effort or the value of quota in steady state. Hence establishment or expansion of aquaculture will be opposed by fishermen in both cases. In the last case they look for the optimal scale of aquaculture and fishing in an ocean area, with an optimal control approach. Aquaculture production and costs are assumed proportional to the area used, and expanding aquaculture area is costly. They assume that the two activities make the same product, and that they share the total market for this product. Hoagland et al characterise and analyse optimal steady state outcomes. Most of their comparative statics findings are as expected. If the marginal effect of aquaculture on carrying capacity for wild fish gets higher, aquaculture should be reduced and fishing effort increased in optimum. However, they find

counter-intuitively, that higher unit cost of aquaculture production gives more area allocated to aquaculture in the optimal outcome (and also a smaller fishing effort).

3   The model

Starting with a Verhulst-Schaefer model of a fishery (see e.g. Clark 1990: 1.1), and a simple model of aquaculture production, we investigate effects of aquaculture on a wild fishery. We consider two ecological effects from aquaculture, working either by affecting the area's carrying capacity for the wild fish population (*model K*), or the intrinsic growth rate of the fish population (*model r*). In addition we consider an effect directly on the efficiency of fishing, assumed to affect the catchability of fishing, technically affecting the catchability coefficient of harvesting (*model q*).

We look at aquaculture-fisheries interactions within a limited geographical area. In most cases aquaculture and fisheries co-exist in a region, and conflicts between them are local rather than regional. We assume there is only one (prospective) marine farmer. The fishery is analysed either as open access or sole-owner. The management area is assumed to correspond to the habitat for the fish stock. We assume that the distribution of fish is unaffected by aquaculture activities. The actors take prices of factors and products as given, being small compared to the market. We look only at steady state. The external effects from aquaculture on fisheries depend on aquaculture production volume directly.

Before looking at the model combining aquaculture and fisheries, we look at aquaculture alone.

3.1 Aquaculture

The marine farmer's optimisation is modelled so that it is independent of what happens in the fishery. Hence, the basic choices made by the marine farmer are common for all variants of the model combining aquaculture and fisheries. We use a simple production volume model, with quadratic cost-function. The function for rents in aquaculture is thus $\pi_a = p_a S - vS^2$, where S is volume produced (by weight), p_a is the price received for units of the farmed product, and v is a cost-coefficient ($v>0$). Marginally increasing costs can be expected if the quality of the localities used for farming is diminishing as production is expanded. Also, when the density of aquaculture plants gets high, more diseases and parasites are likely, reducing overall productivity.

If $p_a - 2vS >0$ for all possible values of S, the marine farmer would like to use the whole available area for farming. For an interior solution, the value of S that maximises rents is $S_a^* = p_a / 2v$. This gives a maximal rent in aquaculture of $\pi_a^* = p_a^2 / 4v$.

3.2 Model K – Carrying capacity externality

This variant has the same form on the externality as in Hoagland et al (2003). The carrying capacity for fish in the area is reduced due to the aquaculture activity.[4] Compared to the basic Verhulst logistic growth function, the natural growth function of the fish stock F(x) is slightly modified:

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[4] Although a positive effect on carrying capacity is also possible, we choose to consider only a negative externality, for ease of presentation.

$$(1) \qquad F(x) = rx\left(1 - \frac{x}{K - \varphi S}\right)$$

Here r is the intrinsic growth rate of the stock x, $K - \varphi S$ is the effective carrying capacity, with K the "natural" carrying capacity, and φ the coefficient of sensitivity by which aquaculture production S influences the effective carrying capacity.[5] A linear relationship between S and effective carrying capacity will in most cases likely be a major simplification.

The harvest rate is given by a Schaefer harvest function: $h = qEx$, where E is fishing effort, and q the catchability coefficient. Under the assumption that aquaculture only expel fish from their habitat to a negligible extent, aquaculture's impact on fish density will be proportional to its effect on fish stock size through K. The Schaefer harvest function can then be used. *Net growth rate* of the fish stock $G(x)$ is then natural growth minus harvest: $G(x) = F(x) - h$. In steady state natural growth of the fish stock equals harvest. Steady state stock as a function of fishing effort is then given by $\bar{x} = (K - \varphi S)(1 - qE/r)$. Higher aquaculture production S gives a lower steady-state stock, for a given level of fishing effort E (remember we assume a negative externality; φ>0).

Assuming constant unit cost c of fishing effort and a constant product price p_f of fish, the rent in fishing is given by: $\pi_f(x, E) = p_f qEx - cE$. Using the steady state stock equation gives an expression of steady state rents, depending on fishing effort E and aquaculture production volume S:

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[5] *K-φS≥0* must be valid for all *S*.

$$(2) \qquad \pi_f(\overline{x}(E), E) = p_f q(K - \varphi S)(E - \frac{qE^2}{r}) - cE$$

We are now in a position to consider the effects of different management regimes for the area, including the fishery. We will assume throughout that only one marine farmer will operate in the area considered. For the fishery we will consider open access and sole owner (rent maximisation). We first consider a case where aquaculture has been given some sort of primary right to decide their level of operation. Fishermen must hence adapt to the marine farmer's choices, but they are allowed to use the area not used for aquaculture. This is contrasted to the case where a social planner decides aquaculture production volume and fishing effort. In the last case a fisherman (or cooperative of fishermen) is given the primary right to the area and any interested in starting up aquaculture must get permission from the fisherman. We open up the possibility of payment for access in the latter case.

3.2.1   Marine farmer has primary right of access

If we are considering *open access* of fishing vessels, the steady state rents from fishing will be zero.[6] Equation (2) can then be equated to zero and solved for the open access effort level:

$$(3) \qquad E^\infty = \frac{r}{q}\left(1 - \frac{c}{p_f q(K - \varphi S)}\right)$$

Clearly, a larger production in aquaculture reduces the steady state effort level (provided $p_f q(K - \varphi S) - c > 0$ - This is the condition for starting fishing on a fish stock at its maximum carrying capacity level, and is assumed fulfilled). This effort level gives steady state stock level $\overline{x}^\infty$ and sustainable yield Y^∞:

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[6] This is here the same as assuming that average revenue equals marginal cost.

$$(4) \qquad \overline{x}^{\infty} = \frac{c}{p_f q}$$

$$(5) \qquad Y^{\infty} = \frac{rc}{p_f q}\left(1 - \frac{c}{p_f q(K - \varphi S)}\right).$$

As usual the steady state stock level is independent of the carrying capacity, and hence here also independent of aquaculture production. The sustainable yield goes down when aquaculture production is increased.

If the fishery has a sole owner, the rent-maximising effort is, taking aquaculture production S as given:

$$(6) \qquad E^* = \frac{r}{2q}\left(1 - \frac{c}{p_f q(K - \varphi S)}\right)$$

As expected $E^* = E^{\infty}/2$. Further, optimal effort is reduced when effective carrying capacity (K-φS) is reduced. Optimal steady state stock $\overline{x}^*$, yield Y^* and rents π^* are then:

$$(7) \qquad \overline{x}^* = \frac{1}{2}\left((K - \varphi S) + \frac{c}{p_f q}\right)$$

$$(8) \qquad \pi_f^* = \frac{r}{4q}\left(\frac{(p_f q(K - \varphi S) - c)^2}{p_f q(K - \varphi S)}\right)$$

$$(9) \qquad Y^* = \frac{r(K - \varphi S)}{4}\left(1 - \frac{c^2}{p_f^2 q^2(K - \varphi S)^2}\right)$$

The steady-state stock level is falling with increasing aquaculture production S.[7] Maximal rents in fisheries fall with increasing S. The sustainable yield falls with increased aquaculture

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[7] It corresponds to the expression in Hoagland et al (2003: 135, (4)), assuming zero discount rate.

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production. If aquaculture production increases, the effect on the maximal rents in fisheries is always negative, but the marginal effect is diminishing.

3.2.2 Social planner

Real life social planners usually consider an array of objectives, and must strike a compromise. Typical objectives are ecological sustainability, to maximise rents, to ensure/maximise employment, or to maximize protein supply. Assume here that a social planner's objective is to maximise joint rents R from fisheries and aquaculture. Given the specifications above this means to maximise R by choosing S and E, or alternatively maximise $\pi_a(S) + \pi_f^*(S)$ by choosing S. If $\partial \pi_a / \partial S + \partial \pi_f^* / \partial S > 0$ for all S, then all the available area should be devoted to aquaculture, and if it is <0 for all S, then only fishing should take place. The condition for an interior solution is:

$$(10) \quad \frac{d\pi_a(S)}{dS} + \frac{\partial \pi_f^*(S)}{\partial S} = 0 \Rightarrow p_a - 2vS = \frac{-r\varphi(c^2 - p_f^2 q^2 (K - \varphi S)^2)}{4 p_f q^2 (K - \varphi S)^2}$$

Solving (10) wrt S gives 3 roots, of which only one is real. None are stated here, as they are all very messy. Analytical interpretation of the real root is not meaningful. What is clear is that the aquaculture production level that maximises joint rents is smaller than what would maximise rents in aquaculture alone. The former takes into consideration that aquaculture has a negative effect on rents in the fishery.

Hoagland et al (2003) find that increased unit cost of aquaculture production in their model gives a larger aquaculture production in optimum. They explain that "the dynamic marginal cost of aquaculture is reduced through an expansion of [aquaculture area and production]" (p.144), and that their model finds a new equilibrium with larger aquaculture area and production, if unit cost of production is increased. To investigate the effect of this in our

model, we find the total differential of the condition in (10), considering changes in *v* and *S,* and rearranging:

$$(11) \qquad \frac{dS}{dv} = \frac{-\dfrac{\partial^2 \pi_a}{\partial S \partial v}}{\dfrac{\partial^2 \pi_a}{\partial S^2} + \dfrac{\partial^2 \pi_f^*}{\partial S^2}}$$

The sign of *dS/dv* is negative, as it is the same as $\partial^2 \pi_a / \partial S \partial v$.[8] If *dv* is positive (unit cost in aquaculture increases), *dS* must be negative (aquaculture production should be reduced in optimum). Our result is the opposite as in Hoagland et al (2003), but in accordance with intuition. Also the other comparative statics results are as expected in our model: *dS/dc* > 0, *dS/dp_f* < 0, *dS/dp_a* > 0 and *dS/dφ* < 0. Increased unit cost of fishing effort *c* reduces aquaculture production *S*. Increased price of fish reduces S. Increased price of farmed fish increases S. Increased marginal effect of aquaculture production on the area's carrying capacity for the wild stock (*φ*) reduces the optimal level of aquaculture production.

3.2.3 *Fisher as "primary rights-holder", with a tradable right*

If a fisher, or cooperative of fishermen, is given primary right to an area, as is the case in some places, prospective marine farmers must ask for permission before starting aquaculture. If negative externalities are expected from aquaculture on the fishery, the fisher will likely refuse the marine farmer access to the area, unless something else can tip the balance. The fisher may demand that the marine farmer pay for using a part of the ocean area, compensating him for negative external effects. To analyse this latter alternative the rent functions must be altered to incorporate costs (for the aquaculture actor) and income (for the fisher) for access for aquaculture to the area.

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[8] This is because the denominator is the same expression as in the second order condition, and must be negative for an interior solution.

$$(12) \qquad \pi_a^t = (p_a - t_a)S - vS^2$$

$$(13) \qquad \pi_{fl}^t = p_f qEx - cE + t_f S$$

Here t_a is the price the marine farmer is considering paying in rent for each unit produced, and t_f is the price the fisher is considering charging. We can only get a solution with both industries present if $t_a \geq t_f$. The first order conditions for maximising rents wrt S are, for the marine farmer and the fisher respectively:

$$(14) \qquad p_a - t_a - 2vS = 0 \Rightarrow t_a = p_a - 2vS$$

$$(15) \qquad \frac{\partial \pi_f^*}{\partial S} + t_f = 0 \Rightarrow t_f = \frac{-\partial \pi_f^*}{\partial S}$$

We see easily that when $t_a = t_f$, we have the same condition as when a social planner maximise joint rents. Having a primary rights holder who can lease the right out further for rent, can realise the overall optimal solution if the actors are well informed.

3.3 Model r – intrinsic growth rate externality

Here we assume that the intrinsic growth rate *r*, rather than carrying capacity *K*, is negatively influenced by aquaculture production. The fish stock growth function now is:

$$(16) \qquad F(x) = (r - \alpha S)x\left(1 - \frac{x}{K}\right)$$

Where $r - \alpha S > 0$ for all possible S. All other relationships are as for model K. We get the following steady-state results for the fishery, given the level of aquaculture production:

Model r	Open access	Rent maximisation
Effort level	$E^{\infty} = \dfrac{r - \alpha S}{q}\left(1 - \dfrac{c}{p_f qK}\right)$	$E^{*} = \dfrac{r - \alpha S}{2q}\left(1 - \dfrac{c}{p_f qK}\right)$
Yield	$Y^{\infty} = \dfrac{(r - \alpha S)c}{p_f qK}\left(K - \dfrac{c}{p_f q}\right)$	$Y^{*} = \dfrac{r - \alpha S}{4K}\left(K^2 - \dfrac{c^2}{p_f^2 q^2}\right)$
Stock level	$\bar{x}^{\infty} = \dfrac{c}{p_f q}$	$\bar{x}^{*} = \dfrac{K}{2} + \dfrac{c}{2p_f q}$
Rents	0	$\pi_f^{*} = \dfrac{r - \alpha S}{4q}\left(\dfrac{(-p_f qK + c)^2}{p_f qK}\right)$

Table 1 – Steady state results in model r.

The sign of the marginal effects of a change in S are the same as in model K, except that $\bar{x}^{*}$ is unaffected by increased S here, but negatively affected in model K.

For the socially optimal production volume in aquaculture, this variant of the model is the only one that gives a reasonably simple expression for it:

$$
\begin{aligned}
(17) \qquad & p_a - 2vS = \frac{\alpha}{4q}\left(\frac{(c - p_f qK)^2}{p_f qK}\right) \\
& \Rightarrow S = \frac{1}{2v}\left(p_a - \frac{\alpha}{4q}\left(\frac{(c - p_f qK)^2}{p_f qK}\right)\right)
\end{aligned}
$$

All comparative statics on this give results as expected.[9]

For the management regime where fishers have primary right to use the area, the results are also similar to in *model K*, and as expected.

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[9] dS/dc>0, dS/dp_f<0, dS/dp_a>0 etc

3.4 Model q – catchability externality

Aquaculture structures and operations might affect fishing operations directly, as is mentioned earlier. The fishing effort required to catch a given amount of fish could change due to the establishment of aquaculture, independent of its impact on fish stock size or density of fish. Fishing effort can be viewed as a composite of several activities related to actual fishing: Preparing vessel and gear for fishing, transport to and from the fishing grounds, getting gear in and out of water, and actual fishing with gear in the water. Although the efficiency of the gear, while it is in the water, could be unchanged by marine farming, the other elements of fishing effort could be affected. This is the situation in "model q" here. We assume that the catchability coefficient in the harvest function is negatively impacted by aquaculture production.

The fish stock growth function now is:

$$(18) \qquad F(x) = rx\left(1 - \frac{x}{K}\right)$$

The harvest function is

$$(19) \qquad h = (q - \beta S)Ex$$

It must be the case that $q - \beta S > 0$ for all S. The steady state results for the fishery are in the table below, again taking aquaculture production as given.

Model q	Open access	Rent maximisation
Effort level	$E^{\infty} = \dfrac{r}{q-\beta S}\left(1 - \dfrac{c}{p_f(q-\beta S)K}\right)$	$E^{*} = \dfrac{r}{2(q-\beta S)}\left(1 - \dfrac{c}{p_f(q-\beta S)K}\right)$
Yield	$Y^{\infty} = \dfrac{rc}{p_f(q-\beta S)K}\left(K - \dfrac{c}{p_f(q-\beta S)}\right)$	$Y^{*} = \dfrac{r}{4K}\left(K^2 - \dfrac{c^2}{p_f^2(q-\beta S)^2}\right)$
Stock level	$\overline{x}^{\infty} = \dfrac{c}{p_f(q-\beta S)}$	$\overline{x}^{*} = \dfrac{K}{2} + \dfrac{c}{2p_f(q-\beta S)}$
Rents	0	$\pi_f^{*} = \dfrac{r}{4(q-\beta S)}\left(\dfrac{(-p_f(q-\beta S)K+c)^2}{p_f(q-\beta S)K}\right)$

Table 2 - Steady state results in model q.

We see that the results follow readily from the other two variants, by just making the appropriate substitution $q = q - \beta S$. The comparative statics analysis of increases in S reveals large differences though. Unlike in the other two variants, increased S gives higher fishing effort under both open access and sole-owner, and higher sustainable yield under open access, given that the stock level corresponding to maximum sustainable yield is larger than the open access steady state stock ($x^{MSY} > \overline{x}^{\infty}$).[10] This is likely the most common situation in exploited fisheries, since world fisheries landings probably have been declining since the 1980s (Pauly et al 2002: 691). However, for a biologically underutilized stock ($x^{\infty} > x^{MSY}$), the effects on effort and yield are the same as in model K.

The effect on steady state stock is also different in model q. In models K and r there are no effect on open access steady state stock of changed S, but in model q it is always positive. A higher production volume gives a larger open access steady state stock here. Likewise,

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[10] Maximum sustainable yield stock larger than open access steady state stock is the same as the condition $K/2 > c/(p_f(q-\beta S))$, or equivalently $p_f(q-\beta S)K - 2c < 0$. This decides the sign of e.g. $\partial E^{\infty}/\partial S = (-r\beta(p_f(q-\beta S)K - 2c)))/(pf(q-\beta S)^3 K)$

increased S in model q gives a larger steady state stock level if the fishery has a sole owner. When aquaculture affects carrying capacity, increased production gives a negative impact on the sole-owner steady state stock level. When it affects the intrinsic growth rate, there is no effect of increased S on the sole-owner steady state stock level.

We will explain these effects by looking at Figure 1 and Figure 2. If the catchability coefficient q is reduced, a larger effort is required to fish a given amount of fish, or equivalently, to get a certain level of total revenues. The total revenue curve is expanded horizontally with reduced q. Hence, with reduced q, effort is increased under open access and sole-owner fisheries. The yield is increased under open access, but decreased under rent-maximisation. While total revenues increase under open access, they are offset by the cost of extra effort. For the sole-owner effort and total costs increase while total revenues decrease. Clearly, rents must be reduced.
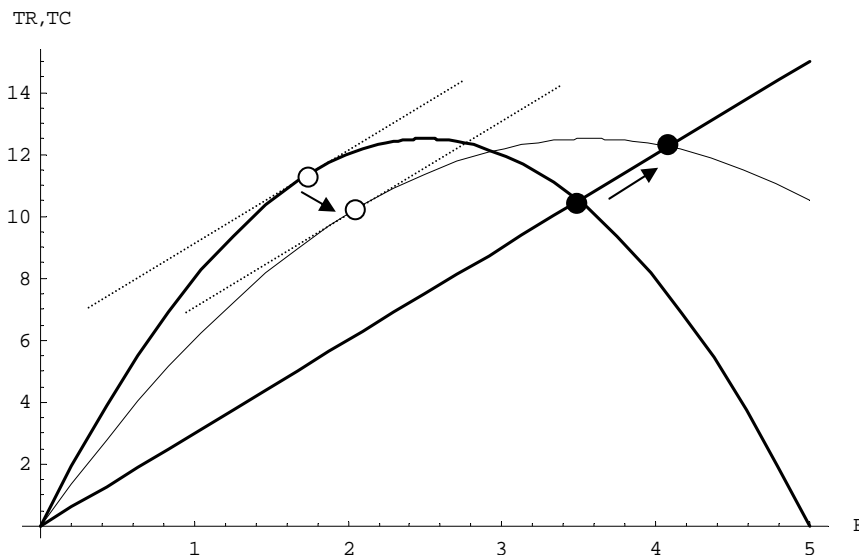
Figure 1 - Steady state total revenues (TR) and total costs (TC) in the fishery as a function of fishing effort, when catchability coefficient q is reduced due to aquaculture. [11] Solid dots are for open access outcome, white dots for sole-owner.

Reduced q means lower catch for given constant effort on a given stock size. Then the stock grows. For the open access case that means an increasing yield for a given effort, as they are fishing on a stock size below maximum sustainable yield (MSY). If the decrease in q was large enough to bring the open access equilibrium below the MSY-point, the effect would be the opposite. In the rent maximising case the yield is always decreasing when q is reduced. As long as the open access case does not get a new steady state stock level below MSY, effort goes up in both cases.

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[11] Hypothetical example with these parameter values: r=0.5, p_f=1, q=0.1, K=100, c=3
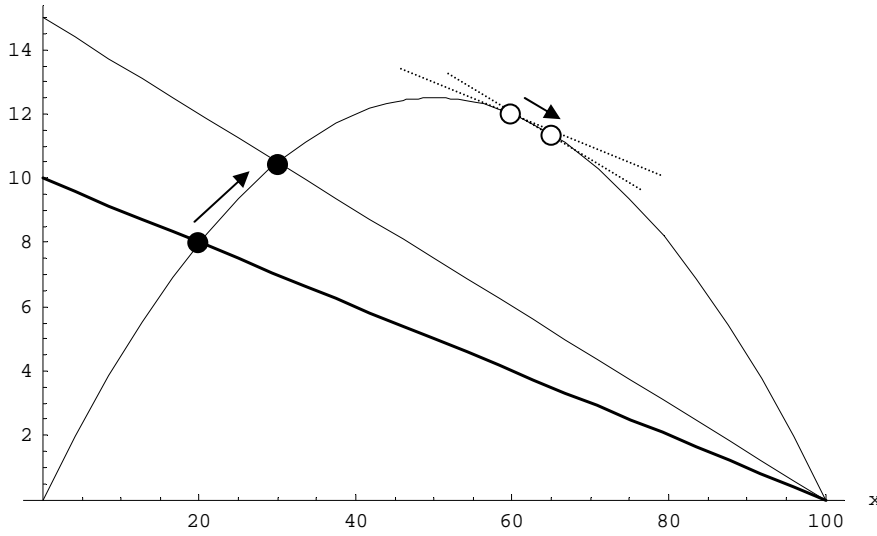
Figure 2 - Steady state total revenues (TR) and total costs (TC) as a function of stock size, when catchability coefficient q is reduced due to aquaculture. Solid dots are for open access outcome, white dots for sole-owner.

In Figure 2, the expression giving total cost as a function of x is $TC = cE = (cr/q)(1-x/K)$, where we have used $h = qEx = rx(1-x/K)$ in steady state. When q is reduced due to aquaculture, the TC-line tilts up, giving new steady state solutions, with changes in steady state stock and sustainable yield as explained earlier.

For the socially optimal production volume in aquaculture, the first order condition for an interior solution here is:

$$(20) \qquad p_a - 2vS + \frac{cr\beta(c - p_f(q-\beta S)K)}{2p_f(q-\beta S)^3 K} = 0$$

Solving for the optimal aquaculture production S gives very messy expressions, which are not open to direct interpretation. Looking at comparative statics effects of changes in parameters however yields interesting results for changes in c:

$$(21) \quad SIGN \frac{dS}{dc} = SIGN \frac{\partial^2 \pi_f^*}{\partial S \partial c} = SIGN \frac{r\beta(2c - p_f(q - \beta S)K)}{2p_f(q - \beta S)^3 K}$$

We see that $dS/dc < 0$ when $\overline{x}^\infty < x^{MSY}$ (and the second order condition wrt S is fulfilled): If

the unit cost of fishing effort *increases*, a social planner should *decrease* aquaculture

production in order to maximise joint rents from aquaculture and fisheries. This immediately

seems to run counter to intuition; if fishing becomes more costly, aquaculture should expand;

if fishing becomes cheaper, fishing should expand and aquaculture be reduced. However, we

see that in a situation where the first order condition (20) is fulfilled, and the unit cost of

fishing effort c then increases, $\partial \pi_f^* / \partial S$ gets reduced. S should then be reduced in order to

increase *(p_a-2vS)* and $\partial \pi_f^* / \partial S$, until the first order condition again is fulfilled.

To understand what is happening, we will compare the situation with and without optimal

adjustment of aquaculture production when c increases, with the aid of figures 3 and 4.[12]

Figure 3 shows how steady state maximal fishing rents (π_f^*), total fishing costs (*TC*), optimal

effort (*E**), aquaculture rents (π_a) and aquaculture production (*S*) varies with unit cost of

fishing c. The thick lines are for constant S, while the thin lines are for S adjusted to

maximise joint rents.

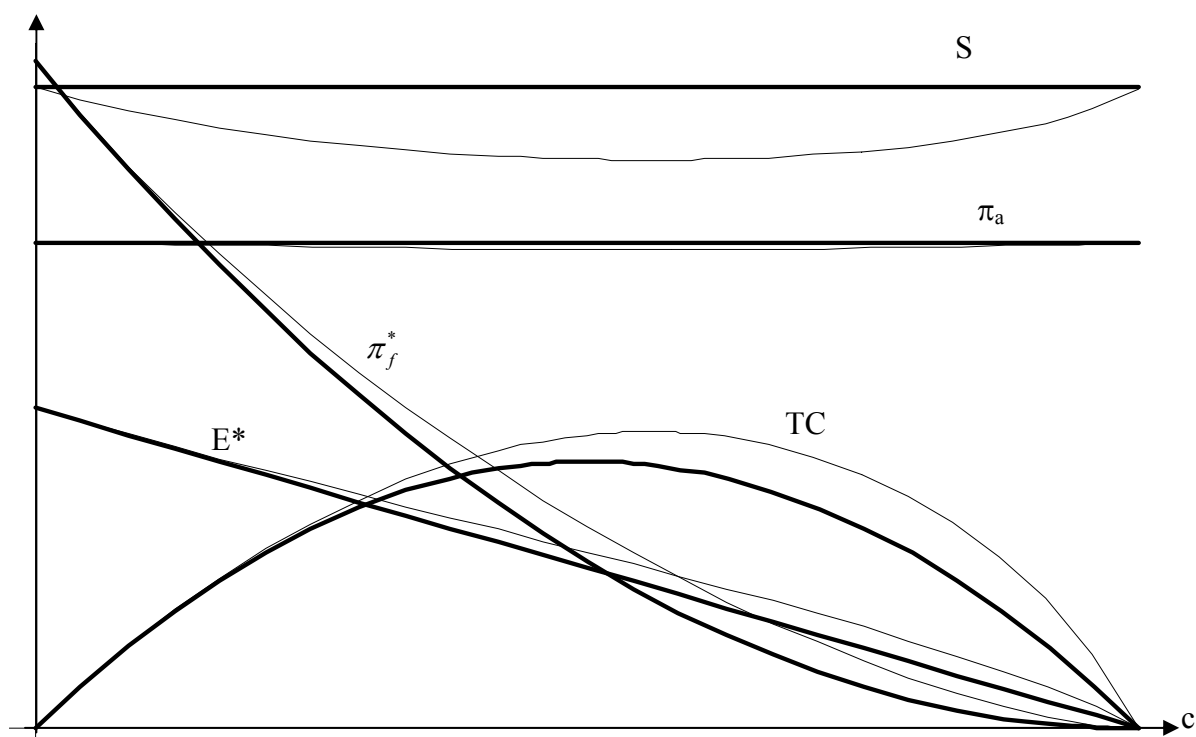[12] The simulations are based on the same parameter values as in Figure 1.

Figure 3 – How variables change with unit cost of fishing effort, when aquaculture production is constant (thick line), or adjusted for maximal joint rents (thin lines). The curves are not to scale.

Let us first look at the case with constant *S*. If *c* increases it will immediately (for unchanged effort) lead to higher *TC*, and lower π_f^*. It is then optimal to reduce fishing effort, as is seen by the thick *E**-line. This gives a somewhat smaller increase in total costs, but also lower revenues. The overall effect is nevertheless still increased *TC* and reduced rents of fishing. We turn to the case where *S* is optimally adjusted. When *c* is so small that $\bar{x}^\infty < x^{MSY}$, a reduction in *S* can counter an increase in *c*. It increases the effective catchability coefficient and increases revenues for a given level of effort. With the higher catchability optimal fishing effort is larger, compared to the case with constant *S*, as is seen by the thin *E**-line. The effect of the optimal adjustment in *S* is to give a smaller reduction in fishing effort, relatively higher

revenues *and* higher total costs, but overall a smaller reduction in fishing rents. Of course, with higher c, fishing rents will always be reduced.

While dE^*/dc is always negative, dE^*/dS goes from negative to positive if $\bar{x}^\infty$ becomes larger than x^{MSY}. Reducing S when $\bar{x}^\infty < x^{MSY}$ is what makes ΔE^* positive. If c is even larger, so that $\bar{x}^\infty > x^{MSY}$, increasing c must now be followed by larger S to make ΔE^* positive. If c gets very large, not even increases in S can keep fishing effort from tending to zero.

Figure 4 shows *differences* in steady state fishing rents ($\Delta\pi_f$), aquaculture rents ($\Delta\pi_f^*$), total fishing costs *(ΔTC)* and rent-maximising fishing effort (ΔE^*), when aquaculture production is optimally adjusted in response to changes in c, compared to when it is set to maximise aquaculture rents only. The price of adjusting S and getting a smaller reduction in fishing rents, is lower rents in aquaculture. The net effect on total joints rents is positive as long as the second order condition wrt S is fulfilled.
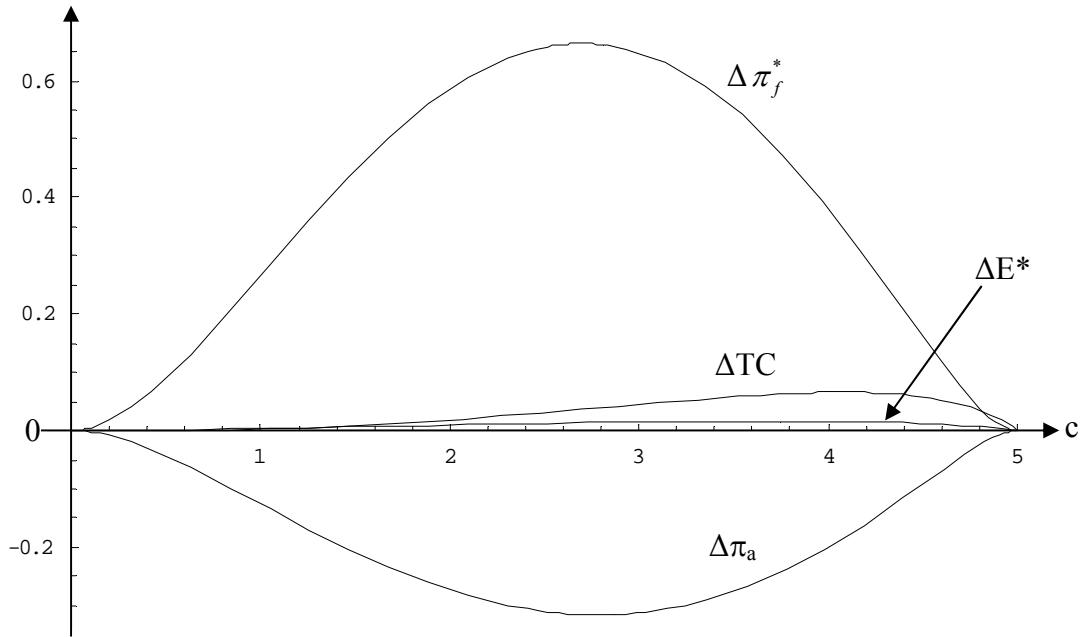
Figure 4 – Differences in variables when optimally adjusting aquaculture production to changes in the unit cost of fishing, compared to aquaculture production being constant.

The other comparative statics results for the case of rent maximisation in *model q* are as expected. When a fisher has primary right to the area, again the socially optimal solution can be realised, given that s/he can lease the right to farm fish out against compensation.

3.5 Comparative statics summed up

In the table below the steady state effects of increased aquaculture production in the three variants of the model are summed up, with respect to fishing effort, stock, yield and rents:

Model $\downarrow$	E^{∞}	$\overline{x}^{\infty}$	Y^{∞}	E^{*}	$\overline{x}^{*}$	Y^{*}	π_f^{*}
K	-	0	-	-	-	-	-
r	-	0	-	-	0	-	-
q	$+$[a]	$+$	$+$[a]	$+$[a]	$+$	-	-

a) *This is the sign if* $x^{MSY} > \overline{x}^{\infty}$. *If* $x^{MSY} < \overline{x}^{\infty}$ *then the partial derivative is negative.*

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Table 3 - Comparative statics of increased S in model K, r, and q, for both the open access case (∞) and sole owner (*). Sign of partial derivatives.

The table shows e.g. that the sign of $\partial E^{\infty} / \partial S$ in model K is negative. The most striking are the positive effects in model q of increased S on fishing effort and stock levels, as well as on yield in the open access case, while the other two variants have no or opposite effect of increased S on the same variables. This is not surprising, though. A reduced q is comparable to restricting the use of very effective fishing gear. This measure has been used to regulate open access fisheries to get higher stocks and yields. However, if the management authority of a coastal area assumes aquaculture impacts negatively on the growth of wild fish, while it actually impacts negatively on the efficiency of fishing, s/he could be very surprised by the effects on fish stock and yield.

4   Discussion and conclusions

This paper is concerned with interactions between marine aquaculture and wild fish fisheries. Such interactions can be of many types, and with positive or negative externalities from aquaculture or fisheries to the other industry. We have presented a model that analyse the effect of externalities from aquaculture to fisheries, on fishing effort, stock-levels, yield and rents in steady state, for both open access and sole-owner fisheries. How different coastal management regimes affect the allocation of resources between the industries is also considered.

Literature cited here shows that aquaculture may affect the physical and chemical environment it is located in, with subsequent effects on the ecosystem. Escapes of farmed species that are also naturally present in the ecosystem could give effects on the genetic

composition of the wild population. Aquaculture can affect fishing costs or operations directly. When farmed products and wild harvested fish are substitutes market interactions are possible. Finally, farming of higher-trophic level species may possibly affect fishing pressure for species used to make feed.

Two variants of the model have an ecological effect of aquaculture on wild fish population, affecting either the habitat's carrying capacity for a fish stock, or the intrinsic growth rate of that fish stock. In the last variant aquaculture affects fishing operations, technically by affecting the catchability coefficient. Previous work has looked at combined market and ecological interactions between aquaculture and fisheries. We believe the setting for the model presented here is more reasonable, as most conflicts between the industries are local, and the actors small, hence taking prices as given.

In theoretical ecology the carrying capacity K is usually attributed to the environment an organism or population lives in (May 1981; 2.2). It hence incorporates such different factors as e.g. nutrient supply, temperature, and the level of competition and predation. The intrinsic growth rate r of an organism or population is attributed to the biology of that organism or population itself. It constitutes a theoretical maximal rate of growth in an ideal environment. Both changes in K and r will affect a population's *actual* rate of growth at different population sizes. However, the equilibrium size of an undisturbed population is entirely determined by K, while the dynamics, the response to disturbances depends also on r. It is hence interesting to consider external effects from aquaculture on both of these, even though we do not present a dynamic analysis here. It is documented that aquaculture activities may affect the environment a fish population lives in, in such ways that modelling these as changes in the area's carrying capacity seems reasonable. This was done in *model K*. A

change in the intrinsic growth rate of a natural fish population can be expected if escapes from aquaculture crossbreed and influence the genetic composition of that population. Hence, modelling effects of aquaculture on *r* may be reasonable in some cases, and this has been done in *model r*. Fishing operations may be affected negatively by aquaculture if the structures set up for farming are rather large, as they may be e.g. for shell-farming, or if they are located particularly obtrusive. In *model q* we assumed that aquaculture affects the efficiency of fishing effort.

We find in our model that a negative externality from aquaculture on an area's carrying capacity, or on the intrinsic growth rate of a fish population, will give reduced fishing effort and yield in steady state, for both an open-access and a sole owner fishery. Steady state stocks are either unaffected or reduced.

If aquaculture has a negative effect on the efficiency of fishing effort, lowering the catchability coefficient in our model, the effects partly depend on whether biological over-fishing is present or not. For the case where open access would lead to biological overfishing (open access stock level is smaller than maximum sustainable yield stock; $\bar{x}^{\infty} < x^{MSY}$), increased aquaculture production leads to higher fishing effort in both open access and the sole owner fisheries, and higher yield under open access. If $\bar{x}^{\infty} > x^{MSY}$ the effects of increased aquaculture will be opposite. If increased aquaculture production lowers the catchability coefficient, it always gives larger steady state stocks, for both open access and sole owner fisheries, and it always gives lower sustainable yield for a sole owner fishery. All the three types of negative externalities described here give reduced rents in equilibrium in an optimally managed fishery. A positive externality of aquaculture on an area's carrying capacity for a fish stock is possible, at least for some types of fish farming, in some

environments. This would of course give opposite effects for model K, of what we have referred above.

We see that different types of externalities can give very different effects on fishing effort, yield and steady state stock, in some cases depending on whether the fishery is open access or sole ownership. These results should be of relevance to managers of coastal areas.

Aquaculture production can of course affect a single fishery in several, or even all, of the ways analysed here. There could even be a positive externality on carrying capacity, but a negative one on catchability. Then both type of externality, sign, and magnitude of the effect matter when allocating use of the coastal area between the two industries.

Different coastal management regimes can affect the trade-off between aquaculture and fishing activities. If marine farmers can set their production level without regarding the negative externality on fisheries, they will choose a too high production volume compared to the socially optimal level. A social planner would consider the negative externality, and make marine farmers produce less, in order to maximise overall rents from the two industries. Inspired by the situation in Japan and New Zealand we have also investigated outcomes if a fisher has primary right to use the ocean area, but may give other users access, possibly against compensation. If there is a negative externality from aquaculture, the fisher has no incentive to allow fish farming, unless compensation is offered. With a tradable right that can be leased or rented from the fisher (the rights holder) to marine farmers, we find that the optimal solution can be realised, if the actors are well informed. It is not very unlikely that marine farmers and fishers are better informed about the external effects between them, than the authorities will be. In New Zealand it will be a group of fishermen that together decide

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whether marine farming will be allowed within a coastal area, and there may be several prospective marine farmers. We have only looked at the case with just one fisher and one prospective farmer.

Hoagland et al (2003) have a dynamic model with an externality from aquaculture on an area's carrying capacity for a wild fish stock, similar to our model her. They find, to their surprise, that increases in the unit cost of aquaculture production leads to a larger aquaculture production in social optimum (and hence also a negative impact on the fishery). They explain that in their model "the dynamic marginal cost of aquaculture is reduced through an expansion of [aquaculture area and production]" (p.144). As a response to the increase in unit cost of production, their model selects a new equilibrium with larger aquaculture area and production, and hence counters the increase in unit cost of aquaculture production. In our *model K*, we get the opposite, intuitive, result: Increased unit cost of aquaculture production should be followed by a reduction in production.

The only seemingly counter-intuitive result we get is in *model q*. To maximise joint rents from aquaculture and fisheries, an increase in the unit cost of fishing effort should be followed by a reduction in aquaculture production. By intuition, we would expect that if fishing becomes more costly, aquaculture should expand. Here we get the opposite result, provided the open access steady state stock would be smaller than the MSY-level. The latter is a common situation in exploited fisheries. An increase in the unit cost of effort increases the total cost of fishing, and lowers rents from fishing. For rent-maximisation, it also implies that fishing effort should be reduced. Now, a reduction in aquaculture production increases the catchability coefficient in fishing. This reduces the fall in revenues due to increased unit cost of fishing, for constant effort. However, it also counters the implied reduction in optimal

level of effort. Despite leading to higher total fishing costs, the result is a smaller reduction in rents from fishing, compared to when aquaculture production is held constant. The smaller reduction in fishing rents, due to reduced aquaculture production, must of course be weighed against the reduced rents in aquaculture due to this. If the open access steady state stock would be larger than the MSY-level, it was optimal to increase aquaculture production if the unit cost of fishing effort went up. This is because the adjustment in optimal fishing effort, in response to changes in the catchability coefficient, switches sign with this condition.

In our model we have assumed that the distribution of fish is unaffected by marine farming, and also that the Schaefer harvest function can be used. These assumptions will not be valid in all settings. Marine aquaculture necessarily occupies some ocean space, both surface area and a volume below the surface. In addition to the physical structures, operation of the farm and any safety zone around it will influence the size of the occupied area. The total area *available* for fishing must be reduced, but the area *used* for fishing could be unchanged. Likewise, the actual habitat for fish could be unchanged or reduced due to aquaculture. Several factors could matter. The type of fish is one, whether e.g. demersal or (semi-) pelagic, or if it is schooling or not. Depending on the type of fish and local fishing conditions, fishing may take place only in some parts of an area. If the areas taken for aquaculture were not fishing areas previously, aquaculture will not affect fishing operations as such. The size and form of the ocean space occupied by aquaculture also matters. If marine farming were to occupy a large part of the coastal area, it would almost certainly affect fishing.

The assumption that the distribution of fish is unaffected by aquaculture activities can be reasonable if the aquaculture structures occupy a negligible part of the total space available to fish. That is, they occupy a small portion of the total area, have a very limited depth in the

water compared to the total depth, or are not in the space used by the fish species in question. An example could be a marine farm using only the top 5 m of a 50 m deep marine environment, and fishing is only for demersal wild fish species using the bottom 5-10 m. It is also often the case that fish populations are non-uniformly distributed over their habitat. Hence fish farms can in many cases be located with none or only minimal impacts on fish populations.

Using the Schaefer harvest function assumes catch per unit effort (CPUE) is proportional to stock size, and remains so for all levels of stock and fishing effort. Among the central assumptions for this hypothesis are that the fish population is uniformly distributed, that fishing gear don't get saturated, and that vessels do not congest (Clark 1990, 222). Implicitly it assumes CPUE to be proportional to density of fish (Flaaten and Mjølhus 2005; 161). If the habitat size for fish would change due to aquaculture activities, this would complicate analysis a lot. If vessels congest, perhaps due to a reduced fishing area because of more aquaculture structures, fishers would experience decreasing marginal returns of fishing effort. Of course, in many real cases aquaculture structures may be located so that fishing operations are not affected at all.

If fishing gets barred from an area due to the establishment of aquaculture, but fish still remain inside the area, this might be viewed as a sort of nature reserve or marine protected area (MPA) regarding the fish. MPAs have received considerable attention in economics literature the latter years (see e.g. Flaaten and Mjølhus 2005). The size of a MPA, and the migration rate between the MPA and the harvest zone, are central for the effects of the MPA on yield, stock size and optimal effort level. Using a MPA-approach here would only be warranted if the area that fishing is barred from, due to aquaculture, is of a considerable size.

We have assumed that the total area of aquaculture farms, or the form or size of individual

farms, is such that a MPA-like approach is *not* necessary.

In summary, we have presented a model to study the effects of several types of external

effects from aquaculture to fisheries, and we have also considered how different coastal

management regimes can affect the choice of activity levels in the two industries. Our results

should be of relevance to coastal managers. Assuming the wrong type of external effect can

give very surprising outcomes, even when all externalities are taken to be "negative". Giving

one industry a primary right to use coastal areas will normally not realise the socially optimal

outcome, unless some sort of tradable rights scheme is possible. The model has several (at

least potential) limitations, among them the assumption that fish distribution is not affected

by aquaculture operations. The properties and outcomes of a tradable rights scheme, when a

fisher has primary rights to an area, should also be investigated in a multi-actor setting.

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# 6 Appendix - Figures for changes in K and r

6.1.1 Figures for changes in K

Figure 5 – When carrying capacity K varies: a) Steady state total revenues (SSTR) and steady state total costs (SSTC) as a function of fishing effort E; b) SSTR, SSTC as a function of stock level; c) Development of E, x, Y when K varies in the open access case; d) Development of E,x,pi,Y when K varies in the profit maximising case.[13]
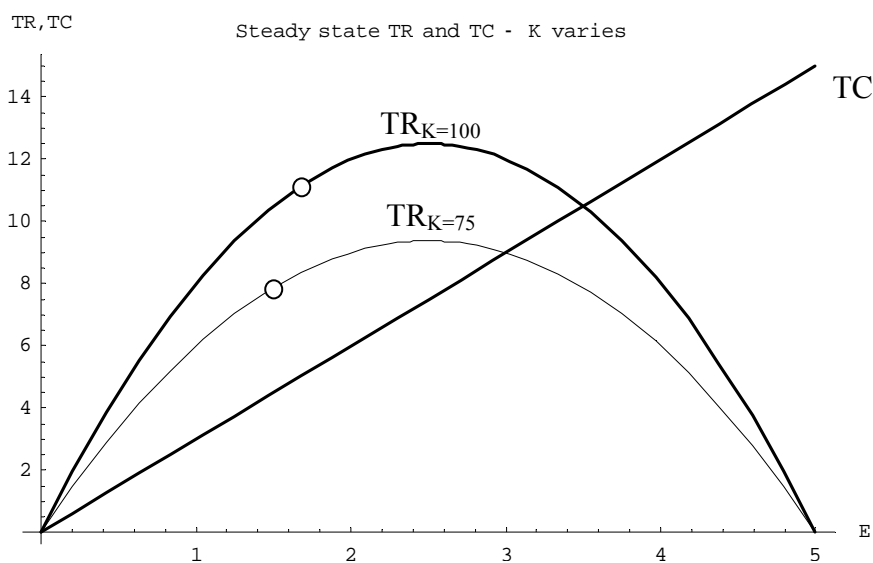
(The following are the points corresponding to maximising profits and to open access, in our two cases, with K=100 and K=75: {Point[{1.75, 11.375}], Point[{1.5,7.875}], Point[{3.5,10.5}], Point[{3.,9.}]}

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[13] Parameters used for the numerical simulations: r=0.5, p_f=1, q=0.1, K=100, c=3, pa=1, w=25, v=1. Alternative values of parameters: K=75, r=0.75,q=0.15, c=2.

Steady state TR and TC, K changes
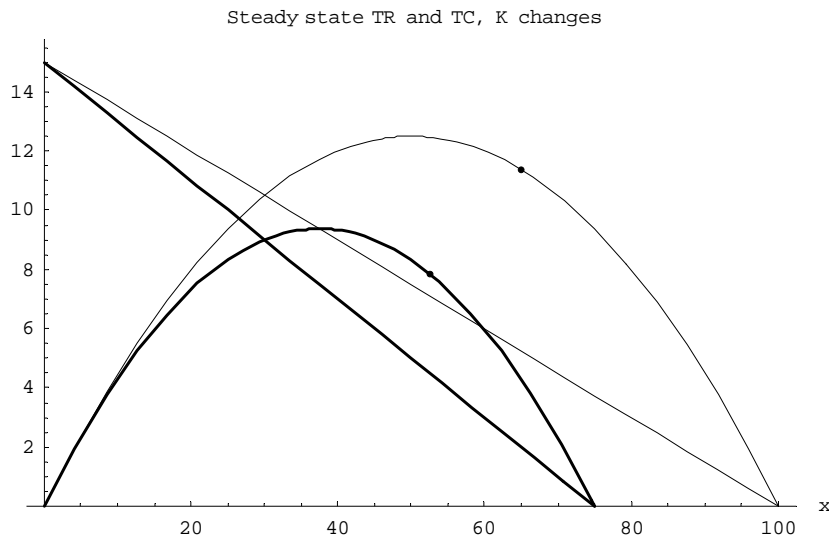
{Point[{65.,11.375}],Point[{52.5,7.875}],Point[{30.,10.5}],Point[{30.,9.}]}

The expression giving TC as a function of x: $TC = cE = (cr/q)(1-x/K)$, using

$h = qEx = rx(1-x/K)$ in steady state.

Increased carrying capacity K moves the steady state total revenue curve up and outwards in the effort diagram. It gives higher effort levels both in the open access and profit-maximising cases. This always gives higher yield. In the profit-maximising case it also gives increased profits. The effects on the steady-state stock size differ though. Under open access the stock size in equilibrium is unaffected by higher carrying capacity, but under profit-maximisation it gets higher with higher K.

6.1.2 Figures for changes in r

Figure 6 - Steady state total revenues (TR) and total costs (TC) as a function of steady state stock size, when intrinsic growth rate r varies.

Steady state TR and TC, r changes
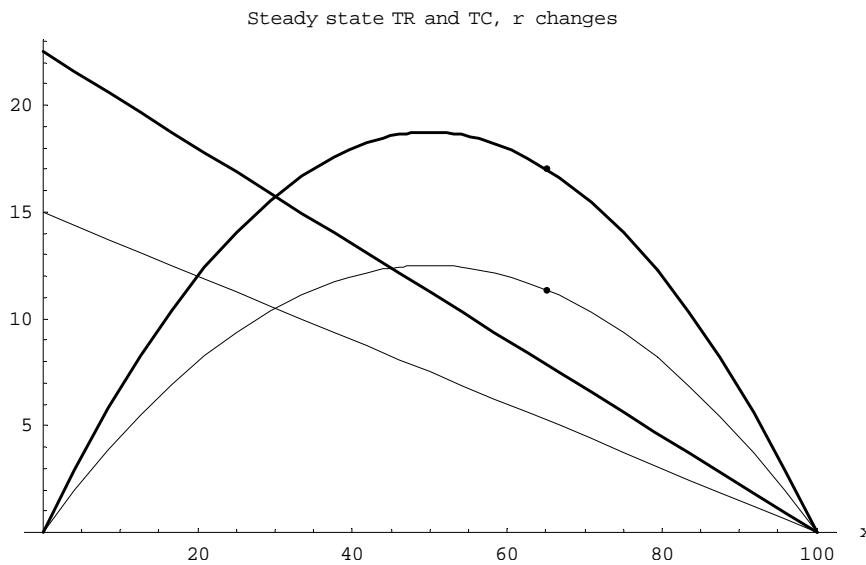
{Point[{65.,11.375}],Point[{65.,17.0625}],Point[{30.,10.5}],Point[{30.,15.75}]]}

Figure 7 - Steady state total revenues (TR) and total costs (TC) as a function of fishing effort, when intrinsic growth rate r varies.

Steady state TR and TC - r varies
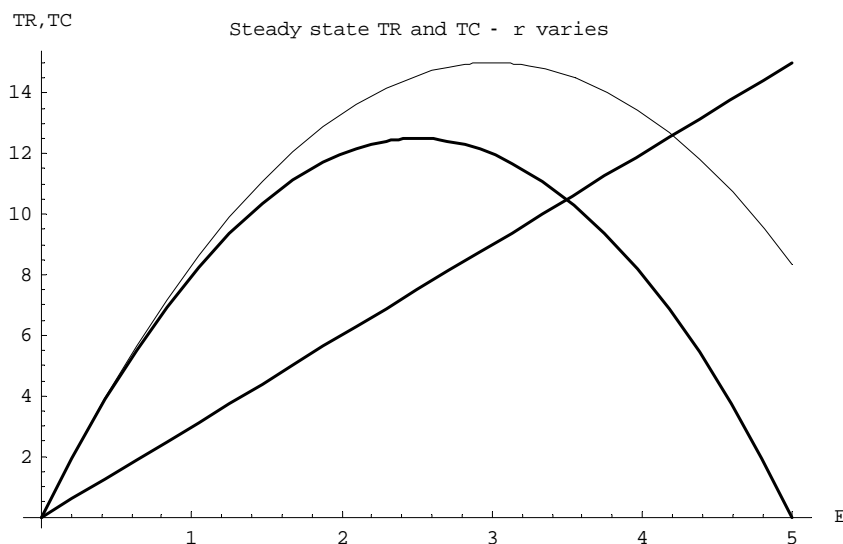
{Point[{1.75, 11.375}],Point[{2.1, 13.65}],Point[{3.5,10.5}],Point[{4.2,12.6}]]}

Increased intrinsic growth rate r bends the total revenue curve upwards, but otherwise its characteristics are unchanged. Higher r gives higher effort, higher yield, but lower steady

state stock, in both the open access and the profit-maximising case. Optimal profits go up with higher r.

7 List of contents