Aquaculture-Fisheries Interactions

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Abstract In this paper, I investigate aquaculture externalities on fisheries, affecting either habitat, wild fish stock genetics, or fishing efficiency under open-access and rent-maximising fisheries. This is done with a Verhulst-Schaefer model of fish population-dynamics and production, coupled with a simple aquaculture production model. Externalities are modelled by letting carrying capacity, the stock's intrinsic growth rate, or catchability coefficient in the fishery depend on aquaculture production. The different externalities can give totally opposite results on steady-state fishing effort, yield, and stock, even for only negative externalities. With a catchability externality, increased unit cost of fishing effort implies reduced aquaculture production to maximise benefits to society under reasonable assumptions. Resource allocation between the industries is analysed under three different coastal management regimes: 1) aquaculture has a primary right of use; 2) joint management of aquaculture and fishery; 3) fishers have a primary right of use, including the right to sell marine farming rights.

Key words Aquaculture, fisheries, externality, interactions, carrying capacity, intrinsic growth rate, catchability coefficient, habitat, genetics.

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Introduction

There is increasing rivalry for coastal resources (Buanes *et al.* 2004). In some cases the rivalry is for access to the same resource; in others 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 (Dwire 1996; Grey and Sullivan 2003; Anon. 2002; Murai 1992). In this paper, I consider the use and management of coastal areas when there are external effects of aquaculture on fisheries.

Over the last 40-50 years, marine aquaculture has grown steadily, in both volume and value (Tacon 2003). Aquaculture can have many different types of environmental effects, most of which researchers have been aware of for more than 20 years (Black 2001). The intention of this work is to analyse how different types of aquaculture externalities can affect open-access and sole-owner fisheries. A very general model is developed to grasp the most important qualitative effects. It can be used for a multitude of externality types. I consider externalities on either wild fish growth dynamics or 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. To the best of my knowledge, no one has previously analysed aquaculture externalities on the intrinsic growth rate or fishing effort efficiency. I assume that conflicts between the industries are local, and that no significant market interactions exist between the actors. My model has fish population dynamics and production based on the classic Verhulst-Schaefer fisheries model (Clark 1990). Only stock size, the area's carrying capacity, and the intrinsic growth rate of

the species determine stock growth in my model. I 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 important for coastal managers.

I also consider how different coastal management regimes affect the allocation of resources between the industries: (1) areas are practically unregulated, with marine farmers setting up their operations without regard to local fisheries, or having been given a primary right of use; (2) a social planner maximises overall profits through joint management of aquaculture and fisheries; (3) fishermen have an "historical" right to an area and can decide 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.

Case (3) is inspired by the situation in Japan (Murai 1992) and New Zealand (Gibbs and Woods 2003). In Japan, fisheries cooperatives are given the rights to areas, and anyone wanting to establish a marine farm must get their permission. Since 2005, fishers in New Zealand have had the primary right to ocean areas when (prospective) marine farmers want access. In neither case is payment for access mentioned in the legislation, but not ruled out as far as I know. I 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.

The paper is organised as follows. In the second section, I review possible types of interactions between aquaculture and fisheries, and economic analyses of such interactions, before I discuss how to model some types of aquaculture-externalities on fisheries. The

model is presented in the third section, first with a carrying capacity externality and then the variants where the intrinsic growth rate and catchability is affected, respectively. The last section contains the discussion and conclusions.

Interactions between Aquaculture and Fisheries

Aquaculture comes in many forms: freshwater ponds or pens, marine cages where the whole life cycle is controlled, and salmon ranching where only the primary stages of fish life are controlled before juveniles are released to the ocean and caught when they return as adults to spawn (Naylor *et al.* 2000; Tacon 2003). An important distinction is between species like mussels, which use nutrients and food naturally in the water, and carnivores like finfish that require feeding. Naturally, with this diversity the effects of aquaculture on the environment, fisheries, and other stakeholders, vary considerably.

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, including those that affect the genetics of populations; 2) direct effects on costs or productivity; 3) interactions through related product markets; 4) aquaculture's demand for feed may affect fishing pressure on fish used in feed production (Black 2001; Cole 2002; Milewski 2001; Naylor *et al.* 2000; ICES 2005).

An overview of interactions is provided, starting with the general literature on classes 1) and 2), and then go on to the economics literature. As we shall see, the economics literature has focused on interactions 2) through 4), as many models include more than one type of interaction. Only one paper that I am aware of considers the type 1) interaction. I then discuss how one can model interactions of types 1) and 2), using the perhaps most widely used bioeconomic fisheries model as a starting point. This justifies the model presented in the next section.

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. Farmed shellfish can compete with other species for nutrients, oxygen, and available sunlight in the water body. This may obviously bring about ecological effects (Milewski 2001). Pearson and Black (2001) give an overview of major environmental impacts of marine fish cage culture. They include impacts due to enrichment of the environment, transferral of pests and diseases, and ecological impacts of escaped fish that are exotic to a region, but still manage to reproduce. More subtle effects are also possible. Some authors have reported lab experiments where coastal cod flee tanks with water in which farmed cod or salmon have been (Saether, Bjorn, and Dale 2007; Bjørn *et al.* 2007). This indicates that fishermen's claims of cod fleeing old spawning grounds after salmon farming started in the vicinity could be correct. However, Bjørn *et al.* (2007) also observed how cod can be attracted to farming pens in the field.

Genetic impacts on a wild fish stock may occur if farmed fish escape and breed with wild fish. An example is salmon. The reproductive fitness in escaped fish is lower than in native fish, but as the stock of farmed fish is much higher than wild stocks in many areas (e.g., Norway), even relatively small fractional escape rates from farms may have significant impact on wild stocks (Youngson *et al.* 2001). Escapes are substantial in some areas. In the period 1989-1995, escaped salmon from farms comprised, *on average,* from 21% to 38% of the fish in spawning stocks in some Norwegian salmon rivers (Lund, Ostborg, and Hansen 1996, quoted in Youngson *et al.* 2001).

Interbreeding between aquaculture escapees and wild populations poses two hazards (Kapuscinski and Brister 2001). In the short run, the fitness and productivity of the wild fish might be reduced by outbreeding depression, giving a loss of local adaptation. This is because maladaptive genes from farmed fish enter the wild population, and coadapted gene-

complexes that have evolved over time may be disrupted. Kapuscinski and Brister (2001) refer to studies on trout, salmon, and largemouth bass that investigate the effects of interbreeding between wild and domesticated populations. The studies show that "interbreeding […] seldom improves performance of fish in natural environments." This is found to be due to lower survival from hatching, less fright response in fry, poorer innate predator avoidance, and changes in aggressive behaviour. While the first three clearly reduce birth rates and increase mortality rates, either increased or decreased aggression could reduce fitness in the wild.

In the long run, genetic variability between natural populations might be reduced if aquaculture escapees, with little genetic variability, interbreed with several wild populations. This might reduce the long-term sustainability of the wild populations, as it makes them simultaneously more vulnerable to environmental change. One might expect that the genes of escaped farmed fish would be quickly purged from natural populations due to their maladaptation. Kapuscinski and Brister (2001) argue against this. They write, "virtually no aquacultural broodstocks have become so intensively domesticated as to assure a high death rate in the wild, and thus, rapid purging of maladaptive genes." Repeated escapes of farmed fish will also counter the ability of natural selection to purge wild populations of maladaptive straits from farmed fish.

Rather than affecting the marine environment and fish ecology, aquaculture activities may affect fishing operations. This could be on both costs and productivity of fishing. That aquaculture structures may displace fishing activities is suggested in Cole (2002), ICES (2002), and in several works cited in Hoagland, Jin, and Kite-Powell (2003). In a report for the Norwegian Ministry of Fisheries, mapping conflicts over the use of areas in the coastal zone, 26% of respondents answered that the main reason for conflicts between aquaculture and fisheries were fishermen being hindered in trawling or placing nets (Anon. 2002). The

answers came from regional and national representatives of fish farmers and fishermen's organisations, as well as the Fisheries Directorate (state agency for both fishing and aquaculture in Norway). Further, 31% of them stated that marine farms located on or near net pen sites (for temporarily live storage of fish), or positions for setting nets, were the main reasons for conflicts. Fishing is not possible right where marine farms are, but the areas actually barred for other users can be much larger due to safety areas around the farms (Maurstad 2002). Due to fisheries concerns, marine farms are sometimes forced to accept other locations than their first choice. This may increase production costs and/or lower productivity.

Now let us turn to economic papers analyzing aquaculture-fisheries interactions. Anderson (1985a) considers salmon ranching and conflicts with commercial fisheries. In sea ranching, fish are released into the ocean for growth after initial aquacultural upbringing. If it is not possible to limit access to the fish, fishermen who harvest the released fish constitute an externality to the ranchers. 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 (1985a) model.

Anderson (1985b) analyses the market interaction between an open-access fishery and aquaculture. Ye and Beddington (1996) build on Anderson's work (1985b) to analyse market interactions with dynamic models. Phuong and Gopalakrishnan (2004) also study a dynamic market interaction between fisheries and aquaculture, with the complicating factor of individual aquaculture production plants polluting the water used by them and other aquaculture production plants. The fish stock is assumed unaffected by the pollution from aquaculture.

When farmed fish are given feed made with their natural prey, aquaculture indirectly affects the fisheries for the same species as is being farmed. In this setting Hannesson (2003) considers if aquaculture can increase the total supply of fish for human consumption. Asche and Tveterås (2004) discuss under which fisheries management regimes expansion of aquaculture could have a negative impact on fish stocks by using feed from reduction fisheries. They also 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.

None of the papers above includes direct effects from aquaculture operations on fish habitat or ecological effects on fish populations, nor do they have direct effects on fishing operations. The only economics paper, of which I am aware, that includes any of this, is Hoagland, Jin, and Kite-Powell (2003). The authors assume that aquaculture operations affect an area's carrying capacity for a wild fish stock. They first investigate effects of this on an open-access fishery, then a fishery optimally managed by individual quotas, and finally when aquaculture and the fishery 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. Fishermen will oppose establishment or expansion of aquaculture in both cases. In the last case, they look for the optimal scale of aquaculture and fishing in an ocean area using optimal control theory. Aquaculture production and costs are assumed proportional to the area used, and expanding that area is costly. The authors assume that the two industries make the same product and share the total market for it. Characterising and analysing optimal steady-state outcomes, most of their comparative statics findings are as expected. However, Hoagland, Jin, and Kite-Powell find that to maximise joint profits, more area should be allocated to aquaculture if the unit cost of aquaculture production increases.

When investigating the possible effects of aquaculture on fisheries, it is reasonable to start with simple, common models of both fish population dynamics and harvest. The logistic biomass growth-function of Verhulst and the Schaefer harvest function are simple and widely used, making them good starting points despite their limitations (Clark 1990).

Although there are some models of the environmental effects of aquaculture, very few exist where the secondary effects have been quantified (say, how nutrient release translates into enhanced primary production) (Silvert and Cromey 2001). Literature that tries to quantify the external effects into fish population dynamics or economic performance is hard to come by. Gibbs (2004) is an exception, presenting a very crude model for making such quantifications. Models predicting qualitative effects of aquaculture on fisheries are really the best that can be achieved at present.

In theoretical ecology, the carrying capacity K is usually attributed to the environment in which an organism or population lives (May 1981). It incorporates nutrient supply, temperature, and the levels 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 therefore interesting to consider external effects from aquaculture on both of these, even though a dynamic analysis is not presented here.

If aquaculture affects the environment in which a fish population lives, it seems reasonable to model the effects as changes in the environment's carrying capacity. If escapees from aquaculture crossbreed and influence the genetic composition of a wild population, affecting birth and mortality rates, and thus fitness and productivity, it is probably better to

model this as a change in the population's intrinsic growth rate. When fishing operations are affected by aquaculture, this is modelled as an effect on the catchability coefficient of the Schaefer harvest function. The harvest function links stock size and fishing effort to harvest levels.

If fishing is barred from an area due to the establishment of aquaculture, but fish remain inside the area, the aquaculture area can be viewed as a sort of nature reserve or marine protected area (MPA) regarding the fish. MPAs have recently received considerable attention in economics literature (Flaaten and Mjølhus 2005). The size of an 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 an MPA approach is warranted only if the area that fishing is barred from due to aquaculture is of a considerable size. I have assumed that the total area of aquaculture farms, or the form or size of individual farms, is such that an MPA-like approach is *not* necessary.

The Model

The Verhulst-Schaefer fisheries model is coupled with a simple model of aquaculture production to investigate effects of aquaculture on a wild fishery. Aquaculture-fisheries interactions are examined within a limited geographical area assuming aquaculture and fisheries co-exist in a region, and conflicts between them are only local. I assume there is only one (prospective) marine farmer, ignoring issues of entry and exit. The fishery is analysed as either open access or sole ownership. The management area is assumed to correspond to the habitat for the fish stock. I presume that the distribution of fish is unaffected by aquaculture activities. The actors, which are assumed small compared to the market, take prices of factors and products as given, and I examine them only at steady state.

The external effects from aquaculture on fisheries depend directly on aquaculture production volume.

Before looking at the model combining aquaculture and fisheries, aquaculture alone is examined.

Aquaculture

Rents in aquaculture is $\pi_a = p_a S - vS^2$, where *S* is volume produced, p_a is the price received per unit of the farmed product, and *v* is a cost coefficient (*v>0*). Marginally increasing costs are expected if farm localities of lower quality must be used to expand production. In addition, when the cage density increases, more diseases and parasites are likely.

If $p_a - 2vS > 0$ for all possible values of *S*, the marine farmer would likely 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 $\pi_a^* = p_a{}^2 / 4v$.

Model K – Carrying Capacity Externality

In this model, an area's carrying capacity for fish is reduced due to aquaculture. Although a positive effect on carrying capacity is also possible, for ease of presentation I consider only a negative externality. Compared to the basic Verhulst logistic growth function, the natural growth function of the fish stock F(x) is slightly modified:

$$F(x) = rx\left(1 - \frac{x}{K_0 - \varphi S}\right) \qquad (1)$$

Here, *r* is the intrinsic growth rate of the stock *x*, $K_0 - \varphi S$ is the effective carrying capacity, with K_0 the "natural" carrying capacity and φ the coefficient of sensitivity by which aquaculture production *S* influences the effective carrying capacity. $K_0 - \varphi S > 0$ must be valid for all *S*. A linear relationship between *S* and effective carrying capacity is likely to be a

major simplification in most cases. This variant has the same form on the externality as in Hoagland, Jin, and Kite-Powell (2003).

The harvest rate is $h = qEx$, where E is fishing effort and q the catchability coefficient. Under the assumption that aquaculture only forces fish from their habitat to a negligible extent, aquaculture's impact on fish density will be proportional to its effect on the fish stock size through the carrying capacity. 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 $\bar{x} = (K_0 - \varphi S)(1 - qE/r)$. Higher aquaculture production S gives a lower steady-state stock for a given level of fishing effort E (remember a negative externality is assumed; $\varphi>0$).

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

$$\pi_f(\bar{x}(E),E) = p_f q(K_0 - \varphi S)(E - \frac{qE^2}{r}) - cE. \qquad (2)$$

I am now in a position to consider the effects of different management regimes for the area including the fishery. A case where aquaculture is given some sort of primary right to decide its level of operation is considered first. Fishermen must 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 both 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 anyone interested in starting up aquaculture must get permission from the fisherman. The possibility of payment for access is opened up in the latter case.

Marine Farmer has Primary Right of Access

Under open-access, the steady-state rents from fishing will be zero. This is the same as assuming that average revenue equals average cost. Equation (2) can then be equated to zero and solved for the open-access effort level:

$$E^{\infty} = \frac{r}{q}\left(1 - \frac{c}{p_f q(K_0 - \varphi S)}\right). \tag{3}$$

Clearly, increased aquaculture production reduces the steady-state effort level (provided $p_f q(K_0 - \varphi S) - c > 0$. This is the condition for starting fishing on a fish stock at its maximum carrying capacity level, and it is assumed fulfilled). This effort level gives steady-state stock level x^{∞} and sustainable yield Y^{∞}:

$$x^{\infty} = \frac{c}{p_f q} \tag{4}$$

$$Y^{\infty} = \frac{rc}{p_f q}\left(1 - \frac{c}{p_f q(K_0 - \varphi S)}\right). \tag{5}$$

As usual, the steady-state stock level is independent of the carrying capacity, and in this case it is 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:

$$E^* = \frac{r}{2q}\left(1 - \frac{c}{p_f q(K_0 - \varphi S)}\right). \quad (6)$$

As expected $E^* = E^\infty / 2$, and rent-maximising effort is reduced when effective carrying capacity (K_0-φS) is reduced. The rent-maximising steady-state stock x*, yield Y^* and rents π^* are:

$$x^* = \frac{1}{2}\left((K_0 - \varphi S) + \frac{c}{p_f q}\right) \quad (7)$$

$$Y^* = \frac{r(K_0 - \varphi S)}{4}\left(1 - \frac{c^2}{p_f^2 q^2 (K_0 - \varphi S)^2}\right) \quad (8)$$

$$\pi_f^* = \frac{r}{4q}\left(\frac{(p_f q(K_0 - \varphi S) - c)^2}{p_f q(K_0 - \varphi S)}\right). \quad (9)$$

The steady-state stock level is falling with increasing aquaculture production S.[2] Maximal rents in fisheries fall with increasing S. The sustainable yield falls with increased aquaculture production. If aquaculture production increases, the effect on the maximal rents in fisheries is always negative, but the marginal effect is diminishing.

Social Planner

Real-life social planners usually consider an array of objectives, and must strike a compromise. Typical objectives are ecological sustainability or maximising rents, employment, or protein supply. Here, I simply assume that the 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 choosing S to maximise $\pi_a(S) + \pi_f^*(S)$

[2] It corresponds to expression (4) in Hoagland, Jin, and Kite-Powell (2003), assuming zero discount rate.

($\pi_f^*(S)$ is (9)). If $d\pi_a / dS + d\pi_f^* / dS > 0$ for all *S*, the entire available area should be devoted to aquaculture. If it is <0 for all *S*, only fishing should take place. The condition for an interior solution is:

$$p_a - 2vS = \frac{-r\varphi(c^2 - p_f^2 q^2 (K_0 - \varphi S)^2)}{4 p_f q^2 (K_0 - \varphi S)^2}. \qquad (10)$$

Fulfilment of the second-order condition depends on parameter values in a way that is not easily interpreted. Solving equation (10) wrt *S* gives three roots, of which only one is real. Analytical interpretation of the real root is not meaningful.[3] 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. The comparative statics results are as expected: $dS/dc > 0$, $dS/dp_a > 0$, $dS/dp_f < 0$, $dS/dv < 0$, and $dS/d\varphi < 0$. Note that $dS/dv < 0$. This is opposite of what Hoagland, Jin, and Kite-Powell (2003) found with their model: if the cost parameter in aquaculture increases, aquaculture production should be *increased* to maximise overall profits. They explain, "…the dynamic marginal cost of aquaculture is reduced through an expansion of [aquaculture area]" (aquaculture production is proportional to the aquaculture area in their model). In my model, there are no dynamic effects, and this could be the reason why the results differ.

Fisher as "Primary Rights-Holder" with Tradable Rights

If a fisher or cooperative of fishermen has the primary right to an area, as is the case in some places, prospective marine farmers must ask permission before starting aquaculture. If negative externalities on the fishery are expected from aquaculture, the fisher will likely refuse the marine farmer access to the area, unless something can tip the balance. The fisher

[3] Anyone interested can contact the author to get the expressions.

may demand that the marine farmer pay for using 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 farmer) and income (for the fisher) for the farmer's access to the area. If we assume payment per unit production in aquaculture:

$$\pi_a^t = (p_a - t_a)S - vS^2 \tag{11}$$

$$\pi_f^t = p_f qEx - cE + t_f S\,. \tag{12}$$

π_a^t and π_a^t are the new rent functions for aquaculture and fishing, t_a is the price the marine farmer is considering paying the fisher for each unit produced, and t_f is the price the fisher is considering charging. A solution with both industries is only present if $t_a \geq t_f$. The first-order conditions for maximising rents wrt *S* are:

$$p_a - t_a - 2vS = 0 \Rightarrow t_a = p_a - 2vS \tag{13}$$

$$\frac{\partial \pi_f^*}{\partial S} + t_f = 0 \Rightarrow t_f = \frac{-\partial \pi_f^*}{\partial S} \tag{14}$$

for the marine farmer and the fisher, respectively.

It is easy to see 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 sell rights of use further can realise the overall optimal solution if the actors are well informed.

Model r – Intrinsic Growth Rate Externality

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

$$F(x) = (r_0 - \alpha S)x\left(1 - \frac{x}{K}\right), \tag{15}$$

where α is the coefficient of sensitivity by which *S* influences *r* (α>0 for negative externality), r_0 is the natural intrinsic growth rate, and $r_0 - \alpha S > 0$ for all possible *S*. All other relationships are as for *model K*. The steady-state results for the fishery are as for *model K*, with *r* replaced by (r_0-αS) and (K_0-φS) replaced by *K*. The sign of the marginal effects of a change in *S* are the same as in *model K*, except that x^* is unaffected by increased *S* here, but negatively affected in *model K*. This variant of the model is the only one that gives a reasonably simple expression for aquaculture production maximising overall benefits:

$$S = \frac{1}{2v}\left(p_a - \frac{\alpha}{4q}\left(\frac{(c - p_f qK)^2}{p_f qK}\right)\right). \tag{16}$$

The second-order condition for this is always fulfilled (-2*v*<0). All comparative statics results are as expected. For the management regime where fishers have a primary right to use the area, the results are also similar to *model K's*, and as expected.

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. This is the situation in *model q* here. It is assumed that the catchability coefficient in the harvest function is negatively impacted by aquaculture production. Fishing effort can be viewed as a composite of several activities related to actual fishing: preparing the 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 in the water may be unaffected by marine farming, other fishing effort activities could be affected.

The fish stock growth function is now:

$$F(x) = rx\left(1-\frac{x}{K}\right). \tag{17}$$

The harvest function is:

$$h = (q_0 - \beta S)Ex, \tag{18}$$

where β is the coefficient of sensitivity by which S influences q ($\beta>0$ for negative externality), q_0 is the "initial" catchability coefficient, and $q_0 - \beta S > 0$ for all possible S. The steady-state results for the fishery follow readily from the other two variants by just making the appropriate substitution of q with (q_0-βS). The expression for socially optimal aquaculture production is, again, not easily interpreted. The second-order condition is always fulfilled if the stock level at open-access equilibrium is lower than the MSY-level ($x^{\infty} < x^{MSY}$).[4] It can, however, be fulfilled also for $x^{\infty} > x^{MSY}$, depending on parameter values.

The comparative statics analysis wrt aquaculture production S reveals large differences compared with the other models. Increased S gives higher fishing effort under both open access and sole ownership, and higher sustainable yield under open access, given that $x^{\infty} < x^{MSY}$. 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). 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 of changed S on steady-state stock is also different in *model q*. In

[4] MSY 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., $dE^{\infty}/dS=(-r\beta(p_f(q-\beta S)K-2c)))/(p_f(q-\beta S)^3K)$.

models K and *r*, there are no effects on open-access, steady-state stock, but in *model q* a higher production volume gives a larger open-access, steady-state stock. In addition, increased *S* gives a larger steady-state stock level if there is sole ownership, opposite the effects in *model K* and *r*.

These effects are explained in figure 1. Reduced *q* means lower catch for a given fishing effort and given stock size. Then, the stock grows. If $x^{\infty} < x^{MSY}$ initially, this then gives increased equilibrium yield under open access. In the figure, the steady-state total revenue curve is expanded horizontally with reduced *q*, and arrows indicate the move to new equilibria. If the reduction in *q* should bring the open-access equilibrium point far enough above the point corresponding to the MSY stock level, the equilibrium yield under open-access would decrease. In the rent-maximising case, the yield always decreases if *q* is reduced. Under both open-access and rent maximisation, equilibrium effort goes up when aquaculture production increases, as long as $x^{\infty} < x^{MSY}$. While total revenues increase under open access, they are offset by the cost of extra effort.[5] For a sole owner, effort and total costs increase while total revenues decrease. Clearly then, rents must be reduced.

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

$$p_a - 2vS + \frac{cr\beta(c - p_f(q_0 - \beta S)K)}{2p_f(q_0 - \beta S)^3 K} = 0. \qquad (19)$$

The expression for the optimal aquaculture production is not easily interpreted.

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[5] To some extent, the results here resemble those in Anderson (1985b). In his model of a competitive aquaculture industry entering the market of fish from an open-access fishery, it also leads to higher fish stock and yield in equilibrium, provided $x^{\infty} < x^{MSY}$. However, in his model this is due to a reduction in price, not reduced catchability. Further, in his model effort goes down while yields go up. In my model, both effort and yield increase.

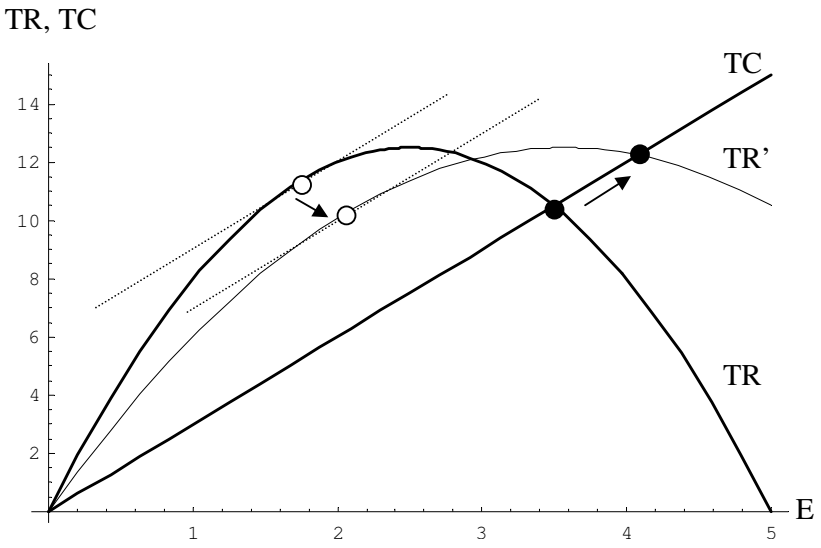

Figure 1. Steady-state Total Revenues (TR) and Total Costs (TC) in the Fishery as a Function of Fishing Effort (E), when the Catchability Coefficient is reduced due to Aquaculture

Note: Solid dots indicate open-access; white dots, rent maximisation. Numbers are from a hypothetical example with these parameter values: r=0.5, p_f=1, q_0=0.1, K=100, c=3, β=0.001, S=0, and S=30.

Comparative statics wrt parameters, however, yields interesting results for changes in *c*. When the second order condition wrt *S* is fulfilled:

$$SIGN\frac{dS}{dc} = SIGN\frac{\partial^2 \pi_f^*}{\partial S \partial c} = SIGN\frac{r\beta(2c - p_f(q-\beta S)K)}{2p_f(q-\beta S)^3 K}. \qquad (20)$$

We see that $dS/dc < 0$ when $x^{\infty} < x^{MSY}$. 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. However, when the first-order condition

(19) is fulfilled and the unit cost of fishing effort *c* increases, $d\pi_f^* / dS$ is reduced. *S* should then be reduced in order to increase $(p_a\text{-}2vS)$ and $d\pi_f^* / dS$, until the first-order condition again is fulfilled. The effect of the optimal adjustment in *S* is to provide a smaller reduction in fishing effort, relatively higher revenues *and* higher total costs, but overall a smaller reduction in fishing rents than without the adjustment in S. Of course, with higher *c*, fishing rents will always be reduced.

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

Discussion and Conclusions

Three variants of a model of aquaculture externalities on fisheries have been presented. 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 third variant, aquaculture affects fishing operations, technically by affecting the catchability coefficient of the harvest function. Previous work has looked at combined market and ecological interactions between aquaculture and fisheries. My model has no market interaction. This setting should be relevant when conflicts are local in nature and actors small, taking prices as given.

I find that the different externality types can provide 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. If the management authority of a coastal area assumes aquaculture impacts negatively on the growth of wild fish, while it actually reduces fishing efficiency, it could be very surprised by the effects on fish stock and yield. These results should be of relevance to managers of coastal areas.

In my model, 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 production lowers fishing efficiency, 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 three types of negative externalities described here give reduced rents in equilibrium in an optimally managed fishery.

In table 1, below, the steady-state effects of increased aquaculture production in the three variants of the model are summed up, wrt fishing effort, stock, yield, and rents.

Table 1

Comparative Statics (sign of derivatives) of Increased S in Models K, r, and q for both Open-Access (∞) and Sole Ownership (*) Cases

	E^{∞}	x^{∞}	Y^{∞}	E^{*}	x^{*}	Y^{*}	π_f^{*}
Model K	-	0	-	-	-	-	-
Model r	-	0	-	-	0	-	-
Model q	+[a]	+	+[a]	+[a]	+	-	-

[a] Sign if $x^{\infty} < x^{MSY}$. If $x^{\infty} > x^{MSY}$, the derivative is negative.

The table shows that the sign of dE^{∞} / dS in *model K* is negative. The most striking is 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 (when $x^{\infty} < x^{MSY}$), while the other two variants have no or opposite effect of increased *S* on the same variables. That the apparently negative effect of

aquaculture on fishing in *model q* actually gives a positive effect on open-access equilibrium stock, yield, and effort is not surprising, though. Reducing *q* is comparable to restricting the use of effective fishing gear. This measure is used to regulate open-access fisheries for higher stocks and yields.

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*, referred to above. Aquaculture production can 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 would matter when allocating between industries.

Different coastal management regimes can affect the tradeoff between aquaculture and fishing activities. If marine farmers can set their production level without regard to a negative externality on fisheries, they will choose a production volume too high 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, I have 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 farming, unless compensation is offered. With a tradable right that can be leased or rented from the fisher (the rights holder) to farmers, the optimal solution can be realised if the actors are well informed. It is likely that marine farmers and fishers know the external effects between them better than the authorities. In New Zealand, groups of fishermen decide together whether marine farming will be allowed within a coastal area, and there may be several prospective marine farmers. Only the case with one fisher and one prospective farmer has been examined.

In my model, I assumed that the distribution of fish is unaffected by marine farming, and that the Schaefer harvest function can be used. Marine aquaculture necessarily occupies some ocean space, both surface area and a volume below the surface. 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. In addition to the physical structures, operation of the farm and any safety zone around it matters, as does the type of fish (e.g., demersal or (semi-)pelagic, schooling or not) and the form of the ocean space occupied by aquaculture. 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 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 10 m of a 50 m deep marine environment, and only demersal fish species using the bottom 5-10 m live there.

Fish populations are usually not distributed uniformly over their habitat. Using the Schaefer harvest function assumes that 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 is not saturated, and that vessels do not congest (Clark 1990). Implicitly it assumes that CPUE is proportional to fish density (Flaaten and Mjølhus 2005). If the habitat size for fish changes due to aquaculture activities, this would complicate the analysis considerably. If vessels congest, perhaps due to a reduced fishing area because of increased aquaculture structures, fishers would experience decreasing marginal returns of fishing effort. In many real cases, aquaculture structures may be located so that fishing operations are not affected at all, and fish populations are only marginally affected.

In summary, I have presented a model to study the effects of several types of external effects from aquaculture on wild fisheries, and I have considered how different coastal management regimes affect the allocation between the two industries. The 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 unaffected 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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