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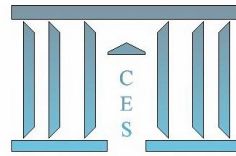
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Is aquaculture really an option?

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Abstract

This article analyzes the impact of the introduction of aquaculture on wild fish stocks and consumer utility, taking into account three key components: (1) the dependence of aquaculture on reduction fisheries for the feeding of the farmed species; (2) biological interactions between the wild edible species –the predator– and the wild feed species –the prey–; (3) consumer preferences for wild and farmed fish. Fisheries are in open access while the aquaculture sector is competitive. We show that when biological interactions are moderate, the introduction of aquaculture is beneficial in the long run: it improves consumer utility and alleviates the pressure on the edible fish stock. Results are deeply modified when biological interactions are strong: the stock of edible wild fish is reduced and the introduction of aquaculture may even cause a decrease in consumer utility. Finally, we explore the consequences of an improvement in aquaculture efficiency and of a sensitivity of consumer preferences to the farmed fish diet, in the case where biological interactions are absent.

Keywords: fisheries, aquaculture, consumer preferences, food security, biological interactions.

1 Introduction

While breeding of terrestrial animals was implemented about 8 000 years ago and substituted to hunting quite rapidly, it took us a very long time to repeat the experience with fish. Aquaculture exists in many parts of the world since the Middle Ages but did not replace fishing until now. However, the increasing needs in food fish make things change rapidly.

The world population growth and the increase in standards of living in developing countries result in a growing demand for animal protein. To keep pace with such demand, wild fisheries are subject to high pressure. According to FAO (2012), in 2009, about 57.4% of world marine fish stocks are estimated as fully exploited and 29.9% as overexploited. An increasing trend in the percentage of overexploited, depleted and recovering stocks is observed since the mid-1970s. In the same way, since the early 1990s, overall landings are marked by a small decline. Many agree that the maximum capture fishery potential from world's oceans has been reached.

In the last three decades aquaculture has been the fastest growing food industry, with an annual average growth rate of 8.8% (FAO, 2012). Focusing on fish production for human consumption, aquaculture has nearly doubled this quantity in recent years. This sector managed to provide 47% of world food fish production in 2010 (FAO 2012). In fact, aquaculture is increasingly viewed as a source of food security. According to the FAO's projections, in order to maintain the current level of per capita consumption of fish protein, global aquaculture production will need to increase by 60% by 2050.

However, the production methods of aquaculture do present certain limitations in terms of environmental sustainability. Aquaculture essential inputs are: land, water, labor, feed and fingerlings. The degree of use of these inputs depends on the characteristics of the production process (whether it is extensive, semi-intensive or intensive), and on the species bred. In any event, inland and coastal farms cause the destruction of natural habitats and erode biodiversity. In addition, the release of untreated water, food and faeces damages wild ecosystems, in particular through pathogene invasions. The use of fertilizers in fish diets produces wastes loaded in nitrogen, phosphorus and other substances inducing eutrophication¹. Regarding fingerlings, they are mainly sourced from the wild rather than derived from hatcheries, occasioning disastrous effects on natural populations (Naylor *et al.*, 2000, FAO, 2012). Finally, aquaculture depends on wild fish stocks for feeding carnivorous and omnivorous species. Fish meal and fish oil, which are key ingredients in aquaculture feed, are made from small oily fish belonging to low trophic levels² (LTL) for about 80% and wastes from processed fish for 20% (Fishmeal Information Network, 2011). Fisheries specialised in catches of prey fish, also termed forage fish, are called reduction fisheries.

¹Eutrophication corresponds to a great increase of phytoplankton, due to the abnormal presence of artificial or natural substances in waters, resulting in the depletion of oxygen in the water, which induces reductions in specific fish and other animal populations.

²Among the species intended to fish meal production there are anchovy, jack mackerel and sardines.

The demand for fish meal and fish oil participates to the fishing pressure drilled on wild stocks. It consumes 19.4% of global marine landings (FAO, 2012). At date, reduction fisheries are described as fully exploited or over-exploited (Grainger and Garcia, 1996; Alder *et al.*, 2008). What is more, Smith *et al.* (2011) emphasize widespread effects of fishing LTL species on marine ecosystems. The study puts forward the trade-off between protecting biodiversity versus contributing to food security, through direct human consumption of LTL species and by providing feed to the agribusiness. The authors support the conclusion that lower exploitation rates of LTL species are required to mitigate ecosystem impacts of reduction fisheries.

Aquaculture is the world's largest user of fish meal and fish oil: in 2009 it consumed 53% of fish meal and 81% of fish oil world production (IFFO, 2011). The sector has succeeded in maintaining a high growth rate in spite of non-increasing landings of feed fish, thanks to important progress in terms of rationalization of fish meal inputs (Asche and Bjorndal, 2011; Shamshak and Anderson, 2008). However, a large increase in aquaculture production is expected, making essential further efficiency improvements in the formulation of fish diets. Especially as reduction fisheries are increasingly targeted for more profitable purposes such as pharmaceutical uses.

Several studies ask about the degree of substitutability between fish meal and plant-based food. Soya meal emerges as a great candidate. It possesses most of the characteristics allowing high flesh quality. However, Kristofersson and Anderson (2006) demonstrate empirically that since the late 90s both types of protein have become poor substitutes, breaking with the strong historical price relationship displayed until then. According to Shamshak and Anderson (2008), beyond some degree of replacement of fish meal by plant-based food, some farmed species are subject to declines in health, growth rate and omega 3 levels due to the lower protein quality and content. The aquaculture industry has recently undertaken the production of a genetically modified salmon species (AquaAdvantage), which growth is enhanced despite very low protein intake. The counterpart of such innovation is that the nutritive properties of the flesh are not conserved. Single cell proteins or zooplankton are considered as potential substitutes to fish meal proteins. Yet, their production costs remain too high to be used in significant amounts in aquaculture feed (Olsen and Hasan, 2012). At date, there does not seem to exist a protein source displaying required properties and profitable at the same time.

Our aim in this paper is to analyze the impact of the introduction of aquaculture on fish consumption, welfare and on the wild fish stocks, taking into account its dependence on wild feed fish and

consumer preferences. The framework retained to investigate these issues is that of a competitive aquaculture sector and open access fisheries.

Motivations for this latter hypothesis are the following. Although the general trend is to tighten regulations, resource management schemes are far from being implemented or efficient worldwide. Furthermore, referring to Costello *et al.* (2012), it appears that countries with several unassessed fisheries, which likely goes along with poor management schemes, have often expanded aquaculture³. The depletion of fishery resources and the subsequent loss in food production potential may have fostered the development of other fish production techniques. In any event, this observation further supports our assumption that farming co-exists with open access fisheries. Overall, it is necessary to analyze mechanisms at work in absence of intervention, especially in order to properly direct management initiatives.

Our model is highly stylized. It consists of the demand side and three sectors: an edible fish fishery, a reduction fishery and an aquaculture sector producing farmed fish.

The characteristics of the technologies at stake for fishing and farming, as well as two types of interactions, namely biological interactions and economic interactions on the marketplace, are essential.

First, consumers can obtain fish by two means: fish can be either fished or farmed. One important question is the relative efficiency of these two technologies in producing edible fish. Another important point is of course the relative cost of the two production methods.

Secondly, we account for biological interactions between fish stocks to reflect the ecosystemic effects of fishing. While the aquaculture sector harvests feed fish to grow farmed fish, the wild edible fish feeds on this same stock. Thus, we investigate how critical is the removal of feed fish for the biomass of the wild edible species and for its supply.

Thirdly, market interactions between wild edible fish and farmed fish arise. Consumers may choose to consume wild or farmed fish, which are strong substitutes, depending on the prices of the two types of edible fish and their preferences.

We derive steady state outcomes from our model as well as the pattern of the trajectories of fish prices, consumption and stock levels to appraise the dynamics resulting of these interactions. Overall, what emerges from our analysis is that when biological interactions are moderate, that

³Personal remark of Christopher Costello to the authors.

is when the wild edible species displays a low degree of food dependence on the feed fish stock, aquaculture increases welfare via a higher total fish supply, and alleviates the pressure on the edible stock, which increases in spite of the fact that the prey species is less abundant. Otherwise, when biological interactions are strong, the harvest of the prey species for the aquaculture industry results in a lower stock and supply of edible fish, and a higher wild fish price. The introduction of the aquaculture food production may even result in lower global fish supply and utility.

In addition, we explore the consequences of an improvement of aquaculture productivity in the case where biological interactions are absent, and show that when the wild species are heavily exploited, this improvement is beneficial.

As we suspect that such an improvement is at least partly achieved by farming less carnivorous species, we finally endogeneize consumer preferences by assuming that they are carnivorous species-biased. Precisely, we study an extension of the model where preferences vary according to the characteristics of the farmed fish, which we link to the productivity of aquaculture technology. Our assumption is the following. On the one hand, the more carnivorous the farmed species is, the more inefficient is its breeding, in the sense that the production of 1kg of flesh requires a lot more than 1kg of wild feed fish. On the other hand, the taste of consumers for the farmed fish depends on its diet: the more carnivorous the farmed species is, the more consumers like it⁴, or the more substitutable to the wild edible fish they perceive it is. It turns out that the improvement of the productivity of aquaculture has a negative side effect: aquaculture farms fish that consumers like less, or find less substitutable to wild fish. We conjecture that in these circumstances there may exist a utility-maximizing farmed species.

A few papers have investigated the market interactions between aquaculture and capture fisheries. Anderson (1985) supposes that the wild and the farmed species are the same, and consequently have the same market price. He shows that in the case of a fishery in open access exploited beyond the maximum sustainable yield, the entry of competitive aquaculturists increases total fish supply, thereby, reducing consumer price and increasing wild fish stock. Indeed, profit loss mechanically reduces fishing effort. Ye and Beddington (1996) assume both goods are imperfect substitutes with positive cross-price elasticities. Similarly, the authors find positive benefits of aquaculture for consumers, via increased fish supply and reduced prices. Yet, the imperfect substitutability

⁴Worldwide, carnivorous species such as grouper, cod-fish, halibut, sole etc. display higher economic values than omnivorous ones (FranceAgriMer, 2012; Alaska Department of Fish & Game, 2010).

between farmed and wild products limits the extent to which aquaculture production impacts the capture fishery activity. Hannesson (2002) considers both market and biological interactions. Like Anderson (1985), he assumes that the edible fish and the farmed fish are the same species. This species feeds on a prey in the wild, which is also the input of the aquaculture activity. The argument of the paper revolves around the comparison between the costs of fishing and farming on the one hand, and the efficiency of the transformation of one unit of feed fish into edible fish in the wild and within the aquaculture technology on the other hand. The author relies on numerical simulations. In open access, total food fish production is found to be slightly higher than without aquaculture, but the wild edible fish stock severely drops relatively to the situation absent aquaculture.

Hannesson (2002) is probably the paper that comes closest to ours. Yet, in Hannesson (2002) the farmed and wild edible fish are the same, and have the same price. One of our main contributions is that we account for an imperfect substitutability of the two types of fish, which allows us to analyze how preferences for wild versus farmed fish intervene in price and market equilibria. Our theoretical setting also allows us to examine the consequences of different degrees of biological interactions on these equilibria. Lastly, our results are general, as we provide an analytical resolution of the model and rely on numerical simulations only marginally.

The remaining of the paper is as follows. Section 2 presents the demand side features. Section 3 describes the two-species biological model we consider. Section 4 derives the short run dynamics and the long run state of the edible fishery in open access, in absence of aquaculture. This constitutes our baseline situation for appraising the impact of the aquaculture activity. In Section 5 we introduce aquaculture and proceed to the coupling of the different sectors. We analyze the resulting steady state, its stability, and compare it to that of the baseline situation. We also examine the consequences of an improvement of aquaculture efficiency. We finally endogenize consumer tastes in Section 6. Section 7 concludes.

2 The demand side

Consumers purchase two types of goods, wild fish and farmed fish, which are imperfectly substitutable. The utility function of the representative consumer at each date t is of the CES type:

$$U(Y_{1t}, Y_{2t}) = \left[(1 - \alpha)Y_{1t}^{1-\frac{1}{\sigma}} + \alpha Y_{2t}^{1-\frac{1}{\sigma}} \right]^{\frac{1}{1-\frac{1}{\sigma}}}, \quad \sigma > 1, \quad \alpha \in]0, 1[\quad (1)$$

with Y_1 the wild fish and Y_2 the farmed one. It is reasonable to assume that the two fish products are strong substitutes. Hence, the elasticity of substitution, σ , is greater than 1.

The budget constraint of the representative consumer is:

$$P_{1t}Y_{1t} + P_{2t}Y_{2t} = I \quad (2)$$

where I represents total expenditures on fish consumption, exogenous and supposed to be stationary, and P_{1t} and P_{2t} are respectively the market price of wild and farmed fish.

When maximizing the utility function with respect to the budget constraint we obtain the following demand functions for the two types of fish:

$$Y_{1t}^d = \frac{I}{P_{1t} \left[1 + \left(\frac{\alpha}{1-\alpha} \right)^\sigma \left(\frac{P_{1t}}{P_{2t}} \right)^{\sigma-1} \right]} \quad (3)$$

$$Y_{2t}^d = \frac{I}{P_{2t} \left[1 + \left(\frac{1-\alpha}{\alpha} \right)^\sigma \left(\frac{P_{2t}}{P_{1t}} \right)^{\sigma-1} \right]} \quad (4)$$

As it is well known when preferences are represented by a CES utility function, the response of Y_1^d (resp. Y_2^d) to a variation of P_2 (resp. P_1) depends on the value of the elasticity of substitution. Here, the two goods are strongly substitutable ($\sigma > 1$). Therefore Y_1^d (resp. Y_2^d) is increasing in P_2 (resp. P_1).

3 Biological interactions

Now, we introduce the possibility of biological interactions between the two wild species. This is only a possibility, and not necessarily the general rule: it may be the case that no biological interactions exist, because both fish stocks belong to totally different geographical areas. Indeed, the Peruvian anchovies constitute the world largest fishery, landings reaching 10% of global fish catches in peak years. It is the most important input in the fish meal and oil industry. By relying on this industry, salmon farming in Norway or pangasius farming in Vietnam do increase pressure on fish resources worldwide but do not impact reduction fisheries at the local level.

Our assumption is that when biological interactions exist between the two wild species, they are of the predator-prey type. Species 1 a high-value species harvested for human consumption — the predator — while species 3 is a low-value non-edible pelagic species — the prey.

We characterize biological interaction by specific functional forms to be able to derive analytical results. The Lotka-Volterra model is commonly used to describe interspecies dynamics in the literature (Sivert and Smith, 1977; Hannesson, 1983, 2002; Hofbauer and Sigmund, 1998). A two-species, non-linear density dependent version of the Lotka-Volterra model is considered:

$$F_1(X_{1t}, X_{3t}) = a_1 X_{1t} - b_1 X_{1t}^2 + d_1 X_{1t} X_{3t} \quad (5)$$

$$F_3(X_{1t}, X_{3t}) = a_3 X_{3t} - b_3 X_{3t}^2 - d_3 X_{1t} X_{3t} \quad (6)$$

where X_1 and X_3 stand for the stock of species 1 and 3. Parameters d_1 and d_3 define the ecological interdependence between the two species, of the predator-prey type: $d_1 \geq 0$, $d_3 \geq 0$. Parameters $b_1 \geq 0$, $b_3 \geq 0$ traduce the fact that the maintenance needs of the biomass grow faster than the ability to acquire food as the biomass increases (Hannesson, 1983). The rate of growth of each species in absence of the other is given by $a_1 \geq 0$, $a_3 > 0$. If $a_1 > 0$, species 1 can survive without species 3. If $a_1 = 0$, species 3 is necessary to the survival of species 1.

Without any human intervention, the system composed of the two fish populations evolves according to:

$$\dot{X}_{1t} = F_1(X_{1t}, X_{3t}) \quad (7)$$

$$\dot{X}_{3t} = F_3(X_{1t}, X_{3t}) \quad (8)$$

It immediately appears that there exists four steady states satisfying $\dot{X}_{1t} = \dot{X}_{3t} = 0$:

1. a steady state where both populations disappear: $\tilde{X}_1 = \tilde{X}_3 = 0$;
2. a steady state where population 1 goes extinct but not population 3: $\tilde{X}_1 = 0$, $\tilde{X}_3 = a_3/b_3$;
3. a steady state where it is the contrary: $\tilde{X}_1 = a_1/b_1$, $\tilde{X}_3 = 0$;

4. an interior steady state where both populations coexist:

$$\begin{aligned}\tilde{X}_1 &= \frac{b_3}{b_1 b_3 + d_1 d_3} \left(a_1 + \frac{a_3 d_1}{b_3} \right) \\ \tilde{X}_3 &= -\frac{d_3}{b_1 b_3 + d_1 d_3} \left(a_1 - \frac{a_3 b_1}{d_3} \right)\end{aligned}$$

The condition of existence of this steady state is:

$$\frac{a_1}{b_1} < \frac{a_3}{d_3} \quad (9)$$

Notice that it is always satisfied if $a_1 = 0$; that is, if species 1 cannot survive without species 3.

We show in Appendix B.1 that when parameters satisfy condition (9), steady states 1, 2 and 3 are unstable, and the stable steady state that prevails in the long run is steady state 4, where both fish populations coexist; when it is not satisfied, the stable steady state is steady state 3, where the prey population is extinct. In the remaining of the paper we make the assumption that absent any human intervention the equilibrium that prevails is the one where both fish populations coexist. Therefore, condition (9) is supposed to be satisfied.

4 The baseline situation: capture fishery alone

We first study the biological and economic features of the capture fishery in absence of aquaculture. This will be useful to appraise the impact of aquaculture activity. In this baseline situation, utility is linear in the quantity of wild fish consumed, and the demand function reduces to:

$$Y_{1t}^d = \frac{I}{P_{1t}} \quad (10)$$

The dynamics of the capture fishery reads:

$$\dot{X}_{1t} = F_1(X_{1t}, X_{3t}) - Y_{1t}^s \quad (11)$$

$$Y_{1t}^s = q_1 E_{1t} X_{1t} \quad (12)$$

and the evolution of the feed stock is given by equation (8). The production function of the fishery, giving the harvest Y_1^s , is the classical Schaefer (1957) production function, where $q_1 > 0$ is the catchability coefficient of the species and E_1 the effort devoted to fishing.

Fishermen profit is given by:

$$\pi_{1t} = P_{1t}Y_{1t}^s - cE_{1t} \quad (13)$$

where c stands for the unit cost of effort.

We make the assumption that the wild resource is in open access. Consequently, fishermen enter the sector until dissipation of the rent (Gordon 1954):

$$\dot{E}_{1t} = \beta\pi_{1t} = \beta(q_1P_{1t}X_{1t} - c)E_{1t}, \quad \beta > 0 \quad (14)$$

The dynamic system composed of equations (11), (12) and (14) allows us to compute the fish supply Y_1^s as a function of its price. We add to this system the equilibrium of the wild fish market at each date: $Y_1^s(P_{1t}) = Y_1^d(P_{1t})$, where $Y_1^d(P_{1t})$ is given by (10). For $E_1/neq0$, eliminating P_{1t} yields the following three-dimensional dynamic system in X_{1t} , X_{3t} and E_{1t} :

$$\begin{cases} \dot{X}_{1t} = F_1(X_{1t}, X_{3t}) - q_1E_{1t}X_{1t} \\ \dot{X}_{3t} = F_3(X_{1t}, X_{3t}) \\ \dot{E}_{1t} = \beta(I - cE_{1t}) \end{cases} \quad (15)$$

If there exists a date t for which $E_{1t} = 0$, the dynamic system reduces to (7)–(8) thereafter.

It immediately appears that there exists four steady states satisfying $\dot{X}_{1t} = \dot{X}_{3t} = \dot{E}_{1t} = 0$:

1. a steady state where both populations disappear: $X_1^* = X_3^* = 0, E_1^* = 0$;
2. a steady state where population 1 goes extinct but not population 3: $X_1^* = 0, X_3^* = a_3/b_3, E_1^* = 0$;
3. a steady state where it is the contrary: $X_1^* = \frac{1}{b_1} \left(a_1 - \frac{q_1 I}{c} \right), X_3^* = 0, E_1^* = \frac{I}{c}$; the condition of existence of this steady state is $I < ca_1/q_1$. Notice that this situation cannot characterize the long term of this economy under condition (9). Indeed, as this condition ensures that both species coexist when there is no human intervention, fishing of the predator (species 1), cannot worsen the long term stock of the prey (species 3).

4. an interior steady state where both populations coexist:

$$X_1^* = \frac{b_3}{b_1 b_3 + d_1 d_3} \left(a_1 + \frac{a_3 d_1}{b_3} - \frac{q_1 I}{c} \right) \quad (16)$$

$$X_3^* = -\frac{d_3}{b_1 b_3 + d_1 d_3} \left(a_1 - \frac{a_3 b_1}{d_3} - \frac{q_1 I}{c} \right) \quad (17)$$

$$E_1^* = \frac{I}{c} \quad (18)$$

The conditions of existence of this steady state in the case of predator-prey interactions ($d_1, d_3 > 0$) are: $\frac{q_1 I}{c} < a_1 + \frac{a_3 d_1}{b_3}$ and $\frac{q_1 I}{c} > a_1 - \frac{a_3 b_1}{d_3}$. Under condition (9), the second one is always satisfied, while the first one may be binding.

Therefore, condition

$$I < I_w(d_1) := \frac{c}{q_1} \left(a_1 + \frac{a_3 d_1}{b_3} \right) \quad (19)$$

gives the maximum revenue that consumers can spend on fish without inducing the extinction of the edible species. This revenue I_w is an increasing function of d_1 , the parameter characterizing the strength of the predator effect. The higher is d_1 , the higher is the surplus growth of species 1 subsequent to a unit intake of species 3. Hence, the more edible fish can be caught.

Notice that at the interior steady state $X_1^* < \tilde{X}_1$ and $X_3^* > \tilde{X}_3$: fishing of population 1 alleviates the predator effect on population 3.

We show in Appendix B.2 that under condition (19), the steady state that prevails is the interior steady state where both wild fish populations coexist in the long run. It is asymptotically stable: for any initial value of the effort below a certain level⁵, the dynamic paths followed by the stock and effort converge to the steady state, which is a stable node or a stable focus, depending on the parameters. When condition (19) is not satisfied, i.e. when the revenue consumers spend on fish is too high, the wild edible species collapses and the steady state that prevails is steady state 2.

⁵Suppose that the initial effort is $E_{10} \geq 1/q_1$. Then, according to the specification of the catch function, the initial catch is $Y_{10} \geq X_{10}$: the entire stock is harvested at once, extinction occurs immediately. Hence the initial effort must be $E_{10} < 1/q_1$.

5 Introducing aquaculture

We now introduce the aquaculture sector, which exploits the stock of pelagic fish as an input, and study the long run outcomes derived from the coupling of the demand side and all three productive sectors. We also identify the nature of the equilibrium of this system. Next, we compare these steady state outcomes to that of the baseline situation. Lastly, we look at the influence of the efficiency of the aquaculture technology on the long run status of both wild fish stocks and welfare.

5.1 The aquaculture sector and feed fishery

Farmers purchase fish meal and fish oil in the form of compounded feed, which are pellets providing nutrients and different supplements to farmed fish. These pellets are produced by a specialized industry. Here, we consider for simplicity that farmers buy feed fish directly to the reduction fishery. It is actually their unique variable input in this model. Other inputs, mainly capital and labor, are supposed to be fixed and normalized to 1. Feed fish is harvested from the prey stock, X_3 , distinct from the predator fish stock exploited for human consumption X_1 . Feed fish harvesting takes place in open access. Its price is set by the equalization of fishermen supply and the demand from aquaculture. Regarding farmers, they are in competition on the farmed fish market. They decide at each date of the feed quantity that maximizes their profit.

The production function of the representative farmer reads:

$$Y_2 = kY_3^\gamma \tag{20}$$

with Y_2 the farmed fish production, Y_3 the input of feed fish, $\gamma \in]0, 1[$ the share of feeds in the production technology of farmed fish. It is set below one to account for the decreasing marginal productivity of feed fish. The parameter $k > 0$ is the efficiency of the aquaculture sector in converting feed fish into farmed fish flesh. It may be interpreted either as the diet of the farmed species or as technical progress. In the first case, a high k means that the aquaculture sector has chosen to farm a rather omnivorous fish species, which does not require too much feed fish to grow. In the second case, a high k implies that a given species can be grown with relatively few feed, more exactly, low animal protein intake. In the remaining of the document we comment our results on the basis of the first interpretation of k — k reflects a specific species diet — in order

to ease understanding.

Notice that k may be related to the well known FIFO (fish in-fish out) ratio, which gives the number of tons of wild fish necessary to produce one ton of farmed fish (including fish oil and fish meal requirements). The FIFO ratio varies quite a lot between surveys. Tacon and Metian (2008) reports an overall FIFO ratio of 0.7. This ratio includes all bred species: crustaceans, carnivorous, omnivorous and herbivorous. At the carnivorous species-group level, the study reports a salmon FIFO ratio of 4.9. Naylor *et al.* (2009) finds fairly close figures to those conveyed in Tacon and Metian (2008). On the other hand, IFFO (2012) finds an overall FIFO ratio of 0.3 and a salmon FIFO ratio of 1.4. In any event, both studies attest of substantial decrease in FIFO ratio since the 90's.

Maximizing their profit, $\pi_{2t} = P_{2t}Y_{2t} - P_{3t}Y_{3t}$, farmers buy feed to produce farmed fish up to the point where the gain provided to the farming industry by a marginal increase in feed input is equal to its cost (i.e. P_{3t}). Given our specification of the production function of aquaculture (20), this yields:

$$\frac{P_{3t}Y_{3t}}{P_{2t}Y_{2t}} = \gamma. \quad (21)$$

Since the feed fishery is also in open access, fishermen enter the sector until dissipation of the rent, and we have the equivalent of equation (14). The unit cost of fishing c is supposed to be the same in the two fishing sectors, as well as the speed of adjustment β .

The fact that revenues from the aquaculture activity are directly proportional to the revenues of the feed industry (equation (21)) allows us to aggregate the aquaculture sector and the feed sector and to write the dynamic system representing the supply of farmed fish as:

$$\begin{cases} \dot{X}_{3t} = F_3(X_{1t}, X_{3t}) - \left(\frac{Y_{2t}^s}{k}\right)^{\frac{1}{\gamma}} \\ \dot{E}_{3t} = \beta (\gamma P_{2t}Y_{2t}^s - cE_{3t}) \\ Y_{2t}^s = k (q_3 E_{3t} X_{3t})^{\gamma} \end{cases} \quad (22)$$

This dynamic system represents the evolutions of the feed fish stock and the effort devoted to fishing the feed species as functions of the price of farmed fish and the aquaculture technology

characteristics only. It can be directly compared to the corresponding system for wild fish:

$$\begin{cases} \dot{X}_{1t} = F_1(X_{1t}, X_{3t}) - Y_{1t}^s \\ \dot{E}_{1t} = \beta (P_{1t}Y_{1t}^s - cE_{1t}) \\ Y_{1t}^s = q_1 E_{1t} X_{1t} \end{cases} \quad (23)$$

where the evolutions of the edible fish stock and the effort depend on the price of wild fish only.

Interactions between the two systems will come from the demands for wild and farmed fish, depending on both prices, and the market equilibria, as we are going to show.

5.2 The coupling

We now suppose that at a given date, let's say $t = 0$, where the wild edible fishery is at the steady state, the aquaculture activity is introduced. The initial effort is supposed to satisfy: $E_{30} < 1/q_3$, so that the entire feed fish stock is not harvested at once. Hence at $t = 0$ wild fishing and aquaculture coexist. In what follows we study the evolution of these two activities over time and the long run equilibria to which the system may converge. A priori, these equilibria may be of four types: one interior equilibrium where wild fishing and aquaculture still coexist, an equilibrium where aquaculture has disappeared, an equilibrium where the wild edible fishery has collapsed, and lastly an equilibrium where both fisheries and aquaculture have collapsed. We are going to focus on the interior equilibrium, the more interesting.

Starting from systems (23) and (22), we introduce demands for both types of fish and the equilibria of the two fish markets. Define

$$A_t = \frac{1}{1 + \left(\frac{1-\alpha}{\alpha}\right)^\sigma \left(\frac{P_{2t}}{P_{1t}}\right)^{\sigma-1}} \quad (24)$$

From (3) and (4), the two demand functions can be written as:

$$P_{1t}Y_{1t}^d = (1 - A_t)I \quad (25)$$

$$P_{2t}Y_{2t}^d = A_t I \quad (26)$$

Hence $A_t \in [0, 1]$ represents the share of consumer expenditures allocated to buying farmed fish,

and $1 - A_t$ the share allocated to buying wild fish. A_t characterizes the market interactions between the fish populations, stemming from consumer preferences, as opposed to the biological interactions studied above. When $A_t = 0$, consumers consume only wild fish. On the contrary, when $A_t = 1$, only farmed fish is consumed. As stated above, we are going to focus on the case where both wild fish populations exist at the steady state, and determine the conditions allowing this co-existence as well as the dynamic properties of this equilibrium. Hence we suppose that $A_t \in]0, 1[\forall t$.

The equilibria on the fish markets read:

$$P_{1t}q_1E_{1t}X_{1t} = (1 - A_t)I \quad (27)$$

$$P_{2t}k(q_3E_{3t}X_{3t})^\gamma = A_tI \quad (28)$$

The ratio of equations (28) and (27) yields:

$$\frac{A_t}{1 - A_t} = \frac{P_{2t}k(q_3E_{3t}X_{3t})^\gamma}{P_{1t}q_1E_{1t}X_{1t}}$$

Replacing the price ratio by its expression as a function of A given by (24) allows us to obtain:

$$\frac{A_t}{1 - A_t} = \frac{\alpha}{1 - \alpha} \left(\frac{k(q_3E_{3t}X_{3t})^\gamma}{q_1E_{1t}X_{1t}} \right)^{\frac{\sigma-1}{\sigma}} \quad (29)$$

The final dynamic system describes the evolutions of the two wild fish stocks and the two efforts exerted. It is obtained by putting together systems (22) and (23), and using (25) and (26) to eliminate $P_{1t}Y_{1t}$ and $P_{2t}Y_{2t}$:

$$\begin{cases} \dot{X}_{1t} = F_1(X_{1t}, X_{3t}) - q_1E_{1t}X_{1t} \\ \dot{E}_{1t} = \beta[(1 - A_t)I - cE_{1t}] \\ \dot{X}_{3t} = F_3(X_{1t}, X_{3t}) - q_3E_{3t}X_{3t} \\ \dot{E}_{3t} = \beta[\gamma A_t I - cE_{3t}] \end{cases} \quad (30)$$

where A_t is given by (29).

The interior steady state associated to this system is characterized by the following equations, giving the two stationary stocks and efforts as functions of A , which is itself a function of these

same variables:

$$\widehat{X}_1 = \frac{b_3}{b_1 b_3 + d_1 d_3} (x_1 + y_1 \widehat{A}) \quad \text{with } x_1 = a_1 + \frac{a_3 d_1}{b_3} - \frac{q_1 I}{c} \quad \text{and } y_1 = \left(q_1 - \frac{d_1}{b_3} \gamma q_3 \right) \frac{I}{c} \quad (31)$$

$$\widehat{E}_1 = \frac{I}{c} (1 - \widehat{A}) \quad (32)$$

$$\widehat{X}_3 = -\frac{d_3}{b_1 b_3 + d_1 d_3} (x_3 + y_3 \widehat{A}) \quad \text{with } x_3 = a_1 - \frac{a_3 b_1}{d_3} - \frac{q_1 I}{c} \quad \text{and } y_3 = \left(q_1 + \frac{b_1}{d_3} \gamma q_3 \right) \frac{I}{c} \quad (33)$$

$$\widehat{E}_3 = \gamma \frac{I}{c} \widehat{A} \quad (34)$$

$$\frac{\widehat{A}}{1 - \widehat{A}} = \frac{\alpha}{1 - \alpha} \left(\frac{k \left(q_3 \widehat{E}_3 \widehat{X}_3 \right)^\gamma}{q_1 \widehat{E}_1 \widehat{X}_1} \right)^{\frac{\sigma-1}{\sigma}} \quad (35)$$

Proposition 1 contains our results concerning the study of the interior steady state. Figure 1 provides a simple representation of these results.

Proposition 1 (i) *A sufficient condition of existence of an interior steady state where wild fishing and aquaculture coexist is:*

$$I < \bar{I} := c \left(\frac{a_1}{q_1} + \frac{a_3}{\gamma q_3} \right) \quad (36)$$

Under condition (36), the interior steady state is unique.

(ii) *Absent biological interactions ($d_1 = d_3 = 0$), the unique interior steady state, when it exists, is globally stable; this remains true when biological interactions are moderate (sufficient conditions for stability are: $d_1 \leq b_3 \frac{q_1}{q_3}$, $d_3 \leq \frac{b_1}{\gamma}$). Besides, whatever the level of biological interactions, if the revenue spent on fish I is sufficiently small, the unique steady state is globally stable.*

(iii) *If $I \geq \bar{I}$, when $d_1 \leq \bar{d}_1 := b_3 \frac{q_1}{\gamma q_3}$, there is no interior steady state; but when $d_1 > \bar{d}_1$ there may exist up to 2 interior steady states.*

Proof. See Appendices A and B.3. ■

Absent biological interactions, the interior steady state, provided that it exists i.e. that condition (36) is satisfied, is unique and globally stable. As one would expect, the threshold \bar{I} is an increasing function of the unit cost of effort and the intrinsic growth rate of each species, and a decreasing function of the catchability coefficient of both fisheries. It also depends on γ , the elasticity of farmed fish production to feed input. The higher γ , the lower \bar{I} , highlighting the fact that the dependence

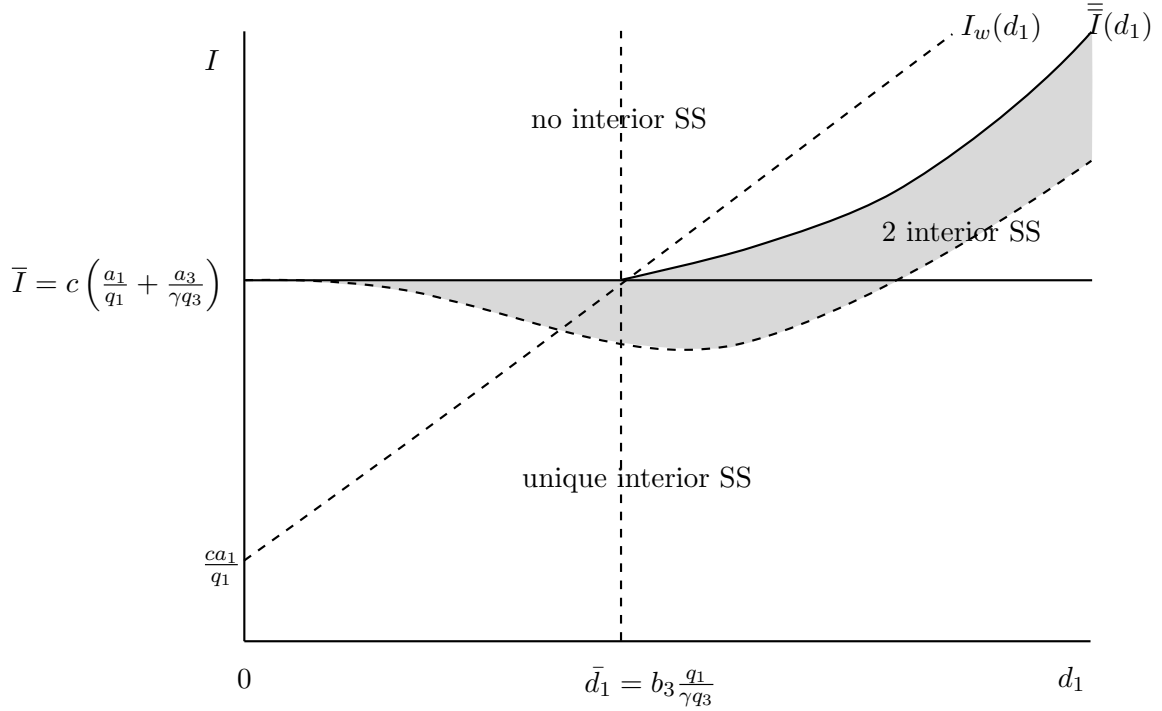


Figure 1: Existence, uniqueness and stability of an interior steady state (shaded zone: instability)

of aquaculture on feed fish must be mitigated for fish production to cope with population growth and increasing demand. Notice that \bar{I} does not depend on k , the parameter characterizing the productivity of the aquaculture technology. When the revenues spent on fish consumption tend towards the threshold \bar{I} both wild fish stocks tend to 0. When I reaches the threshold, we assist to the simultaneous collapse of the edible wild fish stock and the feed one. The relevant steady state is then $\hat{X}_1 = \hat{X}_3 = 0$.

When biological interactions are moderate these results still hold. But stronger biological interactions coupled to a relatively high revenue spent on fish consumption (although smaller than \bar{I}) may provoke instability (see the shaded area in Figure 1). Then the system converges to the steady state where both populations collapse.

For high biological interactions, namely when the parameter d_1 characterizing the predator effect is above the threshold \bar{d}_1 , the revenue that the system can bear is increased above \bar{I} and there may exist two, one or no steady states. More precisely, there exist two steady states for $I < \bar{\bar{I}}(d_1)$ and no steady state for $I > \bar{\bar{I}}(d_1)$, $I = \bar{\bar{I}}(d_1)$ being the limit case (see Figure 1). We were unable to compute analytically the value of $\bar{\bar{I}}(d_1)$, nor to obtain analytical results for the stability of the

steady state(s), so we resort to numerical simulations.

We use the values proposed in Hannesson (2002) for biological parameters, while economic and technological parameters are chosen such that steady state outcomes sketch the state of world resources, market prices and quantities, in relative values. The parameter k is set such that aquaculture is very inefficient, meaning that the farmed species is a high value carnivorous species with a high FIFO. The parameter γ gives feed costs equal to 50% of the aquaculture production value. Such value is likely, though belonging to the upper range values of γ reported by Asche and Bjorndal (2011) for the salmon industry. Parameter α , which weights farmed fish in preferences, is set to 0.4, implying that consumers weight wild fish more than farmed fish. This assumption is grounded on the following argument. First, there exists large empirical evidence that for a given species the price of the wild product is higher than the price of the farmed one (FranceAgriMer, 2012). Furthermore, aquaculture does not actually have the capacity to produce all species existing in the wild. At date, the food fish supply of capture fisheries is much more diversified, which is something consumers value (Quaas and Requate, 2013). Lastly, Nielsen *et al.* (2007) establishes that wild products are perceived to be healthier⁶. Table 1 gives our reference calibration. With this calibration, $\bar{d}_1 = 0.005$ and $\bar{I} = 11$.

Table 1: Calibration

a_1	b_1	d_1	q_1	a_3	b_3	d_3	q_3	σ	c	γ	k	β	α
0.01	0.05	0.02	0.01	0.09	0.01	0.05	0.04	2	2	0.5	0.04	0.05	0.4

We make the assumption that the ratio d_3/d_1 remains the one of the reference calibration above when d_1 varies (i.e. $d_3/d_1 = 2.5$), and compute numerically the region where the steady state is unstable by making I and d_1 vary (see Figure 1).

The simulations also allow us to see that in the region where there exist two steady states, either both are unstable or one of them is unstable and the other stable; in this last case, the stable steady state is the one corresponding to the smaller \hat{A} .

⁶When it comes to farmed salmon, for which market integration has been extensively studied, facts and literature support the idea that consumers are indifferent between wild or farmed products. Going even further, Knapp *et al.* (2007) argues that for a same salmon species, consumers tend to prefer the farmed product for its consistent quality, the reliability of its supply and its more appealing aspect. But farmed salmon is an exception, which experienced a rather unique market story.

5.3 Comparison with the baseline situation

Intuition would lead us to think that the introduction of aquaculture is always beneficial for consumers, whatever their preferences and the efficiency of the aquaculture technology, because more options are offered to them. We are going to show that this is not the case in our model. Such a result can be explained by the fact that both fisheries are in open access, which leads fishermen to take inefficient decisions. Moreover, intuition does not have much to offer about the effects of the introduction of aquaculture on biological populations, on fish price, on the quantities consumed or on the effort devoted to fishing in presence of biological interactions. The following proposition compares the steady state outcomes obtained in the baseline situation where both fish populations coexist (equations (16) to (18)) to those obtained when the wild edible fishery and aquaculture coexist (equations (31)-(35)).

Proposition 2 *Introducing aquaculture leads in the long run to:*

- (i) a smaller total effort devoted to fishing;*
- (ii) a higher stock of edible wild fish and a lower price iff $d_1 < \bar{d}_1$, and vice versa, and a lower feed fish stock in all events;*
- (iii) an ambiguous effect on wild fish consumption when $d_1 < \bar{d}_1$, a decrease of wild fish consumption when $d_1 > \bar{d}_1$, and an ambiguous effect on total fish consumption in all events;*
- (iv) a higher utility when $d_1 \leq \bar{d}_1$, but a possibly negative effect on utility when $d_1 > \bar{d}_1$.*

Proof. See Appendix C. ■

Proposition 2, which results are summarized in Table 2, calls for the following comments.

The total effective long run level of fishing effort is of course $\hat{E}_1 + \hat{E}_3$. We show in Appendix C that there also exists a virtual total level of effort I/c , constant, which must be splitted into an effective effort \hat{E}_1 devoted to catch the edible wild species, and a virtual effort $\hat{E}_3/\gamma > \hat{E}_3$ devoted not only to catch the feed species but also to transform it into edible farmed fish. Total effective fishing effort is smaller with aquaculture than without, whatever the initial state of the edible wild fish stock.

When the predator effect is moderate ($d_1 < \bar{d}_1$), the long run consequences of the introduction of aquaculture are conform to what is expected, and to the results found in the literature (Anderson,

Table 2: Comparison with the baseline

Moderate biological interactions: $d_1 < \bar{d}_1$	Strong biological interactions: $d_1 > \bar{d}_1$
$\hat{E}_1 + \hat{E}_3 < E_1^*$	$\hat{E}_1 + \hat{E}_3 < E_1^*$
$\hat{X}_1 > X_1^*$	$\hat{X}_1 < X_1^*$
$\hat{P}_1 < P_1^*$	$\hat{P}_1 > P_1^*$
$\hat{Y}_1 \begin{cases} > Y_1^* = 0 \text{ when } I_w(d_1) < I < \bar{I} \\ \geq Y_1^* \text{ otherwise} \\ < Y_1^* \end{cases}$	$\hat{Y}_1 < Y_1^*$
$\hat{U} > U^*$	$\hat{U} \begin{matrix} \geq \\ < \end{matrix} U^*$

1985; Ye and Beddington, 1996). That is, the effects of market interactions dominate the effects of biological interactions. The introduction of aquaculture does alleviate the pressure on the wild edible fish stock, in the sense that this stock is higher in the long run with aquaculture than without. It may also lead to a higher *total* fish consumption, which is not surprising and, less intuitively, to a higher *wild* fish consumption. In particular, when $I_w(d_1) < I < \bar{I}$ (see Figure 1), the introduction of aquaculture prevents the collapse of the wild fishery. Finally, the introduction of aquaculture is always beneficial to consumers, whatever their preferences and the efficiency of the aquaculture technology. When biological interactions are moderate, aquaculture is really an option to increase food security.

When the predator effect is strong ($d_1 > \bar{d}_1$) the results are quite different. In this case, the effects of biological interactions dominate those of market interactions. Aquaculture worsens the pressure on the wild edible fish stock and leads to a decrease of total wild fish stocks in the long run. Indeed, as the introduction of aquaculture reduces the stock of feed fish in the long run, less food is left for the predatory species which growth rate decreases. Then, even if species 1 is less harvested, its long run stock decreases because of the shortage of its prey. For the same reason, the introduction of aquaculture, requiring the exploitation of low value fisheries that were not exploited before, has ambiguous effects on total fish consumption and utility. In particular, when $\bar{I} < I < I_w(d_1)$ (see Figure 1), introducing aquaculture may lead to a decrease in welfare, and even to the instability

of the system and the collapse of both fish stocks, which would have survived absent aquaculture.

We illustrate the previous results in the case of a strong predatory effect by numerical simulations, performed with the value of parameters in Table 1, for which $d_1 > \bar{d}_1$. Figure 2 shows the catch of edible fish, the total catch and utility as functions of the revenue I .

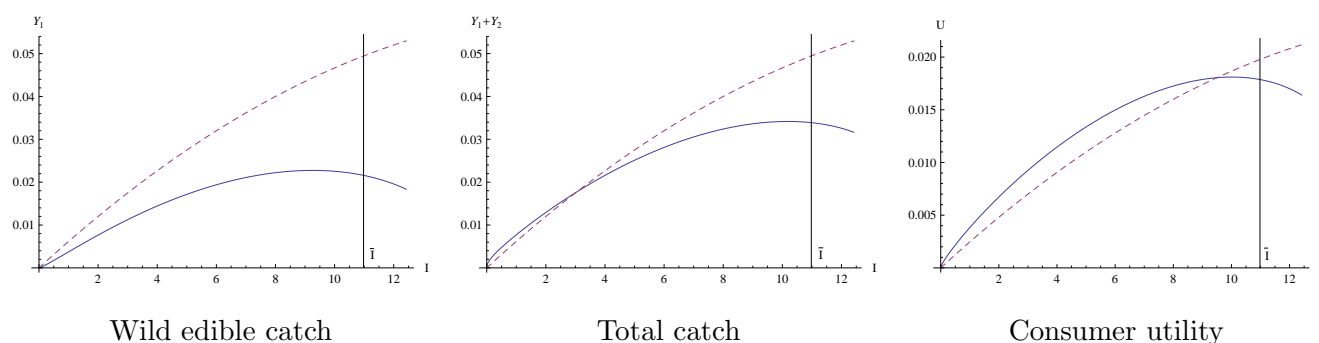


Figure 2: Introducing aquaculture may reduce the long run wild edible fish catch, total catch and welfare (dashed curves: absent aquaculture; plain curves: with aquaculture)

5.4 Improving the efficiency of aquaculture

The efficiency of the aquaculture technology is traduced by parameter $k > 0$, which intervenes in the production function of the aquaculture sector, as it conveys the sector efficiency in transforming low-value feed fish into high-value edible fish (see (20)). As explained earlier, k may be interpreted as the farmed species diet. When k is high the quantity of feed fish required to produce farmed fish is low. This implies that the species farmed is rather omnivorous or herbivorous. Conversely, when k is low the farmed species is a carnivorous one. According to this interpretation, the species of the farmed fish varies with k .

We study the influence of k on the steady state variables, when the wild fishery and aquaculture coexist. To do so, we perform a comparative statics exercise using system (31)–(35), in the neighborhood of the interior steady state. As mentioned earlier, the hypothesis of biological interactions between edible and feed fish stocks is not always effective. Here, we only consider the case where biological interactions are absent (which we can extend to the case where they are moderate), in order to focus on the role of technology.

Proposition 3 *Absent biological interactions,*

(i) Long term stocks, efforts and prices in the edible fish sector and the feed fish sector evolve in opposite directions according to k . As for catches, their evolution depends on the initial state of the fisheries (heavily exploited or not).

(ii) When the wild fish stocks are heavily exploited in the initial steady state, the edible fish stock and catch rise with k at the expense of the feed fish stock and catch, while the effort and the price decrease in the first sector and increase in the second one. The production of farmed fish increases, and its price decreases. As the consumptions of the two edible fish increase, consumer utility increases as well.

Proof. See Appendix D1. ■

The first part of the proposition states that a technological shock in the aquaculture sector will have opposite effects on the two wild fisheries, as far as stocks, efforts and prices are concerned. Intuitively, we could expect that as the aquaculture sector becomes more efficient, the production of farmed fish would increase, its price decrease, and that a substitution effect would induce a decrease of the demand for wild fish, as farmed and wild fish are strong substitutes. But wild fisheries are in open access, and thus not managed on a profit-maximizing basis. Moreover, these fisheries may be heavily exploited, in the sense that stocks are under half their carrying capacity. So the previous intuition, valid for standard man-made goods, may prove very wrong in our case. In fact, we cannot even be sure that farmed fish production will increase and wild fish production decrease in response to a technological shock to aquaculture efficiency.

In the second part of the proposition, we consider an initial steady state where both stocks are heavily exploited. This assumption is convenient since it allows us to obtain clear analytical results. It is also quite relevant, given the state of world fisheries. In this case, the improvement of the aquaculture efficiency is favourable to the edible fishery at the expense of the feed fishery. Effort decreases in the edible fishery while it increases in the feed fishery. Indeed, fishing feed fish becomes more attractive, as a same quantity may be transformed into more farmed fish. Production increases in the edible fishery due to the smaller effort exerted by fishermen in a situation of initial biological inefficiency. Aquaculture production also increases, in spite of the decrease of the catch of feed fish, because of the improvement of the aquaculture efficiency. Utility increases as well.

6 Extension: Endogenous consumer tastes

We now endogenize consumer tastes. We consider that the wild fish product is a highly valued carnivorous species, while the farmed fish can be of any type between a carnivorous species analogous to the wild one to an omnivorous species. Our assumption is that consumer preferences depend on this attribute. A change in k may affect either the weight of the farmed species in the utility function, or the elasticity of substitution between wild and farmed fish, or both.

In equation (1), α is the weight of farmed fish in preferences, and σ is the elasticity of substitution between the wild and the farmed species. We suppose that either α or σ may be a function of k . In the first case, $\alpha(k) \in]0, 0.5]$, meaning that consumers never weight farmed fish more than wild fish, and $\alpha'(k) < 0$, meaning that among farmed species consumers prefer the carnivorous ones. In the second case, we suppose that the lower k the higher σ , meaning that consumers perceive as highly substitutable wild and farmed fish having the same carnivorous diet, but that as the properties of the flesh differs, wild and farmed fish become less substitutable.

The following proposition sums up the consequences of these assumptions.

Proposition 4 *Absent biological interactions, and when consumer preferences depend on k , the effects of an improvement in aquaculture efficiency stated in Proposition 3 are completely reversed, if the weight affected to farmed fish or the elasticity of substitution between wild and farmed fish becomes sufficiently low as the farmed fish becomes less carnivorous.*

Proof. See Appendix D2. ■

Absent any effect of k on consumer preferences, the weight affected by consumers to each product –wild and farmed– in utility is invariant, and the elasticity of substitution between wild and farmed fish as well. The effect of k is simply a productivity effect: the higher k , the more efficient the aquaculture technology. Now, when consumer preferences depend on k (through the weight α or the elasticity of substitution σ), a preference effect adds to the productivity effect: increasing k means not only having a more efficient aquaculture technology but also breeding fish that consumers like less, or that are less substitutable to wild fish. As k increases, the preference effect may progressively dominate the productivity effect. Thereby, when the farmed species is very carnivorous and the wild fish stocks are heavily exploited, increasing k i.e. choosing to breed a

less carnivorous species benefits to the edible fish stock, at the expense of the other stock. Indeed, increasing the substitute availability releases pressure on the wild edible fish stock. But increasing k too much reverses the process.

As a consequence, our conjecture is that there exists a utility-maximizing farmed species type. Consumers being sensitive to the properties of the flesh consumed, it is no use for the aquaculture sector of producing a less carnivorous species, else consumers will be trapped between a highly valued wild product, whose consumption is limited, and a cheap farmed fish they dislike.

We verify numerically that this situation may actually happen, in the case where the weight affected to the farmed fish in the utility function depends on k . We use the following specification:

$$\alpha(k) = \frac{0.5\alpha_{\min}}{\alpha_{\min} + (0.5 - \alpha_{\min})k}, \quad 0 < \alpha_{\min} < 0.5 \quad (37)$$

with α_{\min} the minimum weight affected to the farmed fish. Numerical simulations are performed with the same parameters as in Table 1, except that $d_1 = d_3 = 0$ and $\alpha_{\min} = 0.05$. Figure 3 shows the two wild fish stocks and utility as functions of k .

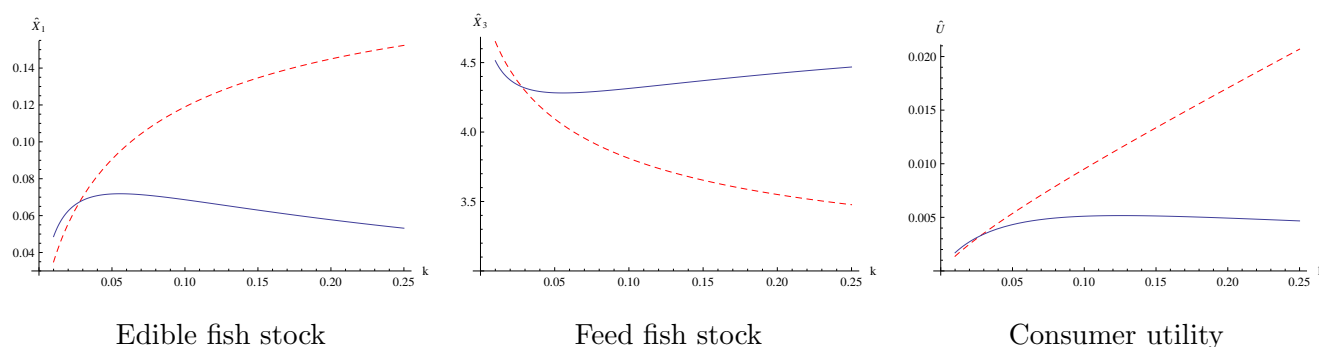


Figure 3: Long run effects of an improvement of aquaculture's efficiency, absent biological interactions (dashed curves: productivity effect alone; plain curves: productivity and preference effects)

7 Conclusion

Many hopes are placed on aquaculture. This production technology is expected to bring more food security by increasing or at least maintaining the current per capita level of fish protein given

population growth, and to alleviate fishing pressure on wild edible fish stocks. This article analyzes the impact of aquaculture on wild fish stocks and on consumer welfare. By means of a two-species Lotka-Volterra model for biological interactions and a simple modeling of the aquaculture technology, we provide some answers to these issues. We find that under the condition of coexistence of aquaculture and the edible fishery, which relates to income, the coupling of all three sectors yields a unique steady state. Nonetheless, while in absence of biological interactions the equilibrium is always stable, it is not necessarily the case when introducing species interdependencies. Indeed, stability is conditional on the intensity of biological interactions and on the income level.

Actually, most of our results regarding the impact of aquaculture entry are conditional on the degree of dependence of the wild edible species on the feed fish stock. When this interaction is moderate, by increasing global fish supply, aquaculture decreases the price of the wild product, thus, fishing effort decreases allowing the edible stock to recover despite the fact that aquaculture exploits the prey species as a production input. In fact, there even exists a range of income levels for which the introduction of aquaculture prevents the wild edible species of collapsing. On the other hand, the feed fish stock is always lower as one can expect. Otherwise, it is not obvious analytically whether total wild fish consumption increases in all event, yet, this low interactions scenario benefits to consumers whose utility is always increased.

In the case where biological interactions are high, aquaculture leads to a decline in the feed fish stock and the wild edible fish stock, a decrease in wild edible fish supply and an increase in its price. Indeed, when assuming a strong dependence of the predator species on the feed fish population, aquaculture threatens the edible species by altering its food web. We find that for high levels of income, aquaculture actually provokes the collapse of the wild edible fishery though it would have remain alone. The net effect of farming on total fish consumption and welfare is ambiguous. We show through numerical simulations that the introduction of aquaculture may decrease utility. Such result can be explained by the fact that the fisheries are supposed to be in open access, meaning that the exploitation of resources is economically inefficient. In this situation, the introduction of aquaculture adds an extra inefficiency which may lead to a decreased utility, in spite of the fact that more consumption options are offered to consumers.

Aquaculture is often criticized on the basis that it is a very inefficient production process. FIFO ratios remain high, even if they have dramatically decreased over the last 15 years, and it seems desirable to lower them further to produce more from a limited input. We study the effects of

efficiency gains in the aquaculture sector, and show that when wild fish stocks are initially heavily exploited, they lead to an increase in the production of wild and farmed fish and, consequently, to an increase in utility. Nevertheless, IFFO believes that aquaculture can continue to decrease its use of fish oil but that there are physiological limits preventing from going below a certain limit depending on the species. According to OECD a potential answer to the limited supply of feed would be to split the salmon market for instance into a cheap market fed with reduced fish oil and an expensive one fed with real Omega 3 fish oil. Differentiating supply through two lines of quality could better match consumers willingness to pay for food fish and better ensure the prosperity of the industry.

Lastly, we emphasize the influence of consumer preferences. Following empirical evidence, we suppose that preferences are carnivorous species-biased, and we link this characteristics of preferences to the efficiency of aquaculture: the more efficient aquaculture is, the less carnivorous is farmed fish and the less consumers like it, or the less substituable to wild fish it is. This leads to a trade-off in the choice of the farmed species, and we suspect that there will exist a farmed species diet that maximizes utility. Indeed, it realizes the optimal balance between quantity available and expected flesh properties.

Beyond the limited supply of feed, other factors are expected to slow aquaculture growth such as land scarcity, stricter regulations or consumer awareness of the sector ecological impacts. Consumer concern for environment or health may affect their behaviour towards farmed products. More evidence on how consumers perceive farmed fish could shade light on the perspectives of food fish production processes.

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Appendix

A Proof of Proposition 1, (i) and (iii)

Plugging the expressions of stationary stocks and efforts given by (31)–(34) into (35) yields:

$$\frac{q_1 (\gamma q_3)^{-\gamma}}{k \left(\frac{\alpha}{1-\alpha} \right)^{\frac{\sigma}{\sigma-1}}} \left(\frac{I}{c} \right)^{1-\gamma} \left(\frac{\hat{A}}{1-\hat{A}} \right)^{\frac{1}{\sigma-1}} \hat{A} \frac{b_3}{b_1 b_3 + d_1 d_3} (x_1 + y_1 \hat{A}) = \left(-\hat{A} \frac{d_3}{b_1 b_3 + d_1 d_3} (x_3 + y_3 \hat{A}) \right)^\gamma \quad (38)$$

Figures 4 and 5 portray the two members of this equation, in the different cases that may occur, depending on the value of the parameters. The left-hand side member is denoted $f(\hat{A})$ and the right-hand side member $g(\hat{A})$. We have $\bar{d}_1 = b_3 \frac{q_1}{\gamma q_3}$.

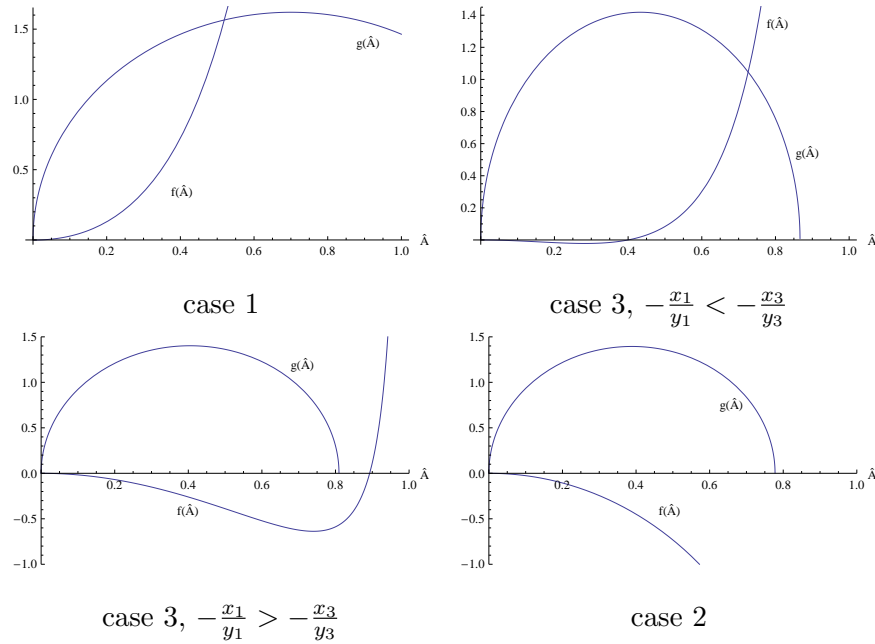


Figure 4: Existence and uniqueness of an interior solution when $d_1 < \bar{d}_1$

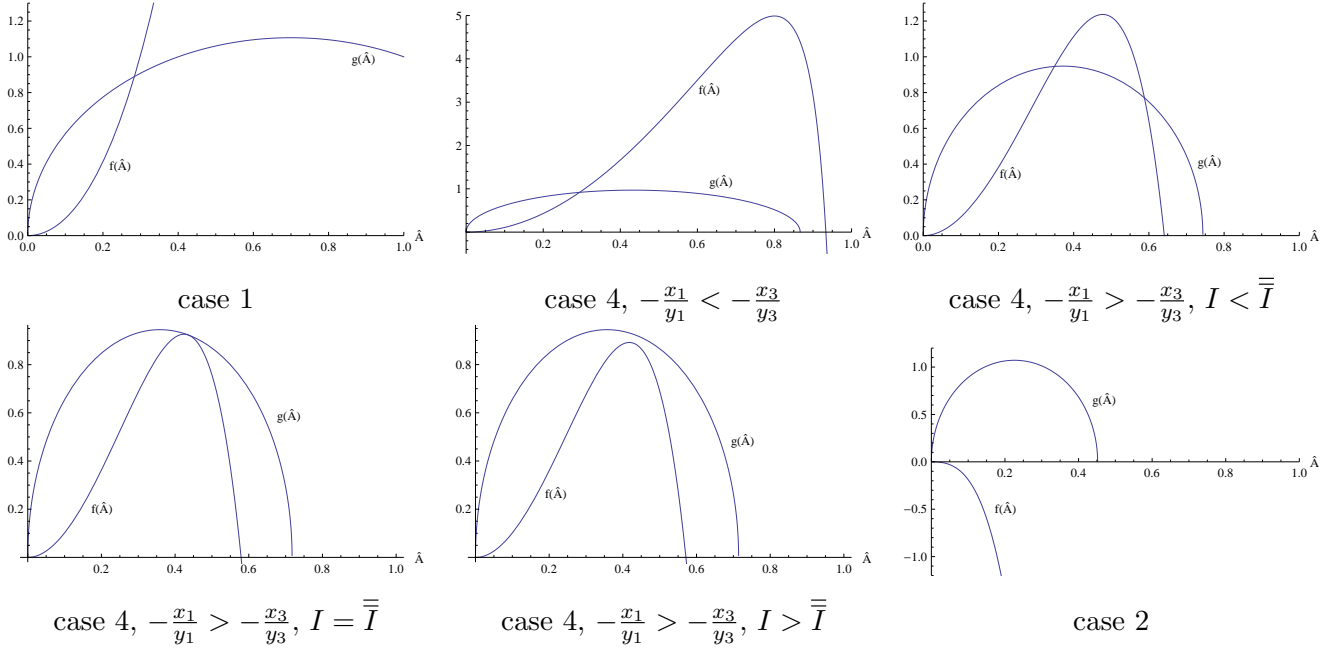


Figure 5: Existence and uniqueness of an interior solution when $d_1 > \bar{d}_1$

Since $d_3 > 0$, $x_3 < 0$ and $y_3 > 0$ (see (31) and (33)), the condition of existence of $g(\hat{A})$ is $x_3 + y_3 \hat{A} \leq 0$ i.e. $\hat{A} \leq -\frac{x_3}{y_3}$. $g(\hat{A})$ is then a positive inverted U-shaped function, with $g(0) = g\left(-\frac{x_3}{y_3}\right) = 0$, and, since $\gamma < 1$ and $-d_3 x_3 > 0$, $g'(0) = +\infty$.

As for the $f(\cdot)$ function, we have

$$f'(\hat{A}) = \frac{q_1 (\gamma q_3)^{-\gamma}}{k \left(\frac{\alpha}{1-\alpha}\right)^{\frac{\sigma}{\sigma-1}}} \left(\frac{I}{c}\right)^{1-\gamma} \left(\frac{\hat{A}}{1-\hat{A}}\right)^{\frac{1}{\sigma-1}} \frac{b_3}{b_1 b_3 + d_1 d_3} \left[\frac{1}{\sigma-1} \frac{1}{1-\hat{A}} (x_1 + y_1 \hat{A}) + x_1 + 2y_1 \hat{A} \right]$$

hence

$$\lim_{\hat{A} \rightarrow 0} f'(\hat{A}) = 0^+ \text{ if } x_1 > 0, 0^- \text{ if } x_1 < 0$$

$$\lim_{\hat{A} \rightarrow 1} f'(\hat{A}) = +\infty \text{ if } x_1 + y_1 > 0, -\infty \text{ if } x_1 + y_1 < 0$$

- *Case 1.* When $x_1 > 0$ and $x_1 + y_1 > 0$, $f(\hat{A})$ is a positive function, increasing from 0 to $+\infty$ when \hat{A} increases from 0 to 1. The solution to equation $f(\hat{A}) = g(\hat{A})$ exists and is unique.
- *Case 2.* When $x_1 < 0$ and $x_1 + y_1 < 0$, $f(\hat{A})$ is a negative function, decreasing from 0 to $-\infty$ when \hat{A} increases from 0 to 1. There exists no solution to equation $f(\hat{A}) = g(\hat{A})$.

- *Case 3.* When $x_1 < 0$ and $x_1 + y_1 > 0$, which requires $y_1 > 0$, $f(\hat{A})$ is first decreasing and then increasing, has two roots 0 and $-\frac{x_1}{y_1} > 0$, and tends to $+\infty$ when \hat{A} tends to 1. In this case, the solution to equation $f(\hat{A}) = g(\hat{A})$ exists and is unique iff $-\frac{x_1}{y_1} \leq -\frac{x_3}{y_3}$, and there is no solution if $-\frac{x_1}{y_1} > -\frac{x_3}{y_3}$. Notice that when $-\frac{x_1}{y_1} \nearrow -\frac{x_3}{y_3}$, $\hat{A} \nearrow -\frac{x_3}{y_3}$ and $\hat{X}_1, \hat{X}_3 \rightarrow 0$.
- *Case 4.* When $x_1 > 0$ and $x_1 + y_1 < 0$, which requires $y_1 < 0$, $f(\hat{A})$ is first increasing and then decreasing, has two roots 0 and $-\frac{x_1}{y_1} > 0$, and tends to $-\infty$ when \hat{A} tends to 1. In this case, there may exist two, one or no solution to equation $f(\hat{A}) = g(\hat{A})$. When $-\frac{x_1}{y_1} > -\frac{x_3}{y_3}$ the solution is unique. When $-\frac{x_1}{y_1} \searrow -\frac{x_3}{y_3}$ there are 2 solutions, a strictly positive one ($\hat{X}_1, \hat{X}_3 > 0$) and a second one characterized by $\hat{X}_1, \hat{X}_3 \rightarrow 0$.

We have

$$\begin{aligned}
 x_1 &= a_1 + \frac{a_3 d_1}{b_3} - q_1 \frac{I}{c} \\
 x_1 + y_1 &= a_1 + \frac{a_3 d_1}{b_3} - \frac{d_1}{b_3} \gamma q_3 \frac{I}{c} \\
 \frac{x_1}{y_1} - \frac{x_3}{y_3} &= \frac{b_1 b_3 + d_1 d_3}{b_3 d_3 y_1 y_3} q_1 \gamma q_3 \frac{I}{c} \left(\frac{a_1}{q_1} + \frac{a_3}{\gamma q_3} - \frac{I}{c} \right)
 \end{aligned}$$

Notice that $\frac{x_1}{y_1} - \frac{x_3}{y_3}$ has the same sign as $\frac{1}{y_1} \left(\frac{a_1}{q_1} + \frac{a_3}{\gamma q_3} - \frac{I}{c} \right)$.

Simple computations based on the previous observations allow us to obtain the results summarized below and portrayed on Figure 6:

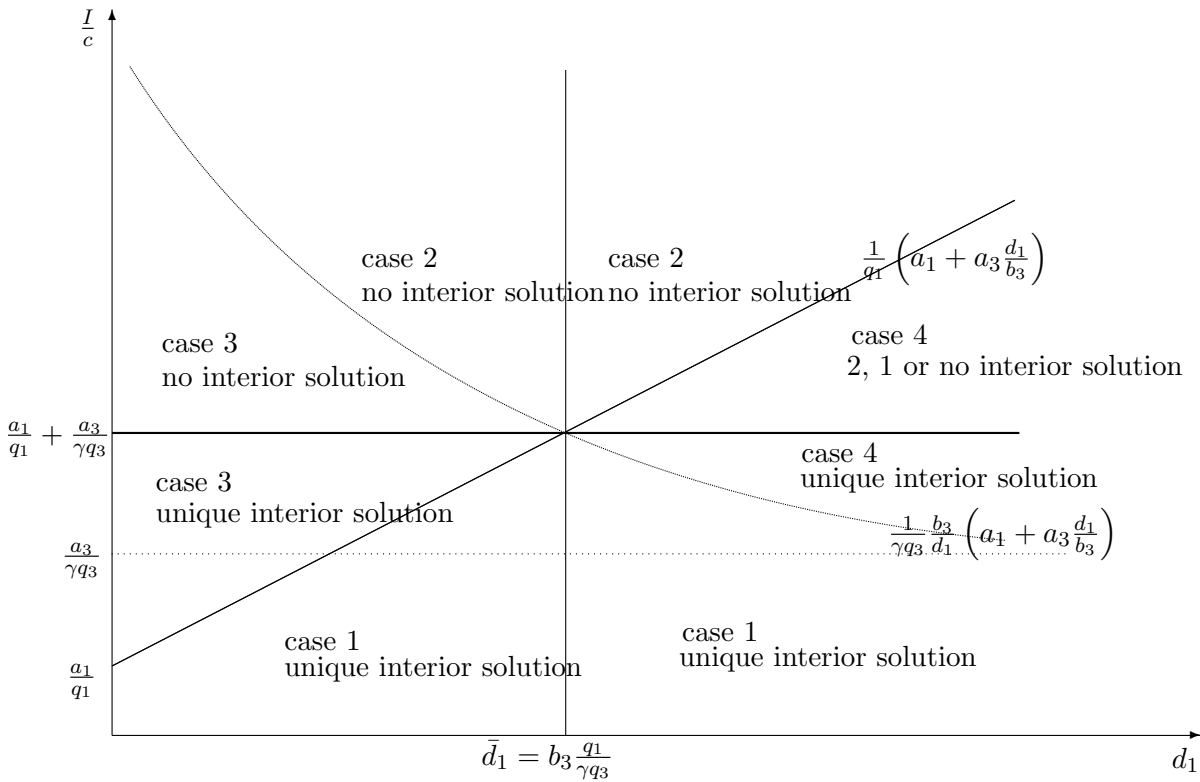
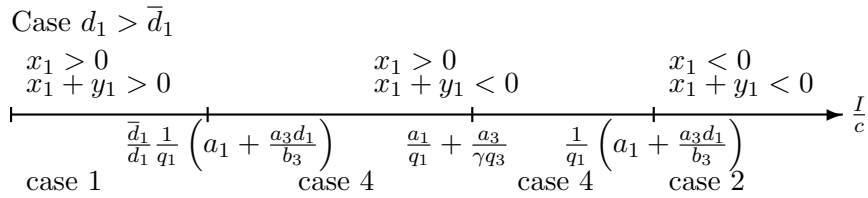
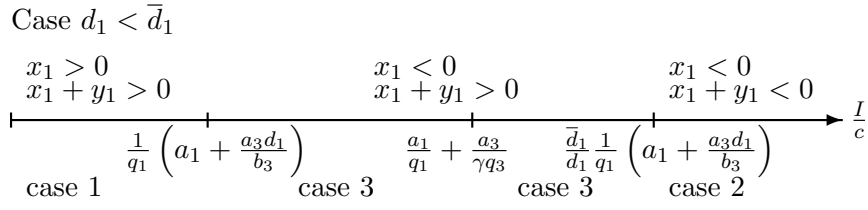


Figure 6: Interior solutions

This proves points (i) and (iii) of Proposition 1.

B Stability

B.1 No fishing

The linearization of the dynamic system (7)–(8) around a steady state yields the following Jacobian matrix:

$$\tilde{J} = \begin{pmatrix} a_1 - 2b_1\tilde{X}_1 + d_1\tilde{X}_3 & d_1\tilde{X}_1 \\ -d_3\tilde{X}_3 & a_3 - 2b_3\tilde{X}_3 - d_3\tilde{X}_1 \end{pmatrix}$$

It immediately appears that steady states 1 and 2 are unstable: the eigenvalues evaluated at these steady states are respectively $a_1 > 0$, $a_3 > 0$ and $a_1 + \frac{a_3 d_1}{b_3} > 0$, $-a_3 < 0$. As for steady state 3, the eigenvalues are $-a_1 < 0$, $a_3 - \frac{a_1 d_3}{b_1}$. Hence steady state 3 is asymptotically stable iff $a_3 - \frac{a_1 d_3}{b_1} < 0 \iff \frac{a_1}{b_1} > \frac{a_3}{d_3}$. Notice that this condition is the opposite of condition (9) of existence of steady state 4. Finally, for steady state 4 we have:

$$\begin{aligned} \det \tilde{J} &= b_1 b_3 + d_1 d_3 > 0 \\ \text{tr} \tilde{J} &= -b_1 - b_3 < 0 \end{aligned}$$

Therefore the two roots of the characteristic equation are either real and negative or complex with a negative real part, depending on the sign of the discriminant, that reads: $(b_1 - b_3)^2 - 4d_1 d_3$. Steady state 4 is a stable node in the first case, a stable focus in the second one. Notice that the first case occurs when biological interactions are mild ($d_1 d_3$ small), and vice versa.

B.2 Capture fishery alone

The Jacobian matrix of the dynamic system (15) linearized around a steady state is:

$$\begin{aligned} J^* &= \begin{pmatrix} \left. \frac{\partial F_1(X_1, X_3)}{\partial X_1} \right|_{X_1^*, X_3^*} - q_1 E_1^* & -q_1 X_1^* & \left. \frac{\partial F_1(X_1, X_3)}{\partial X_3} \right|_{X_1^*, X_3^*} \\ 0 & -\beta c & 0 \\ \left. \frac{\partial F_3(X_1, X_3)}{\partial X_1} \right|_{X_1^*, X_3^*} & 0 & \left. \frac{\partial F_3(X_1, X_3)}{\partial X_3} \right|_{X_1^*, X_3^*} \end{pmatrix} \\ &= \begin{pmatrix} a_1 - 2b_1 X_1^* + d_1 X_3^* - q_1 E_1^* & -q_1 X_1^* & d_1 X_1^* \\ 0 & -\beta c & 0 \\ -d_3 X_3^* & 0 & a_3 - 2b_3 X_3^* - d_3 X_1^* \end{pmatrix} \end{aligned}$$

As it is the case without human intervention, steady states 1 and 2, characterized by the extinction of both wild species or the extinction of species 1, the predatory edible wild fish, are unstable: the eigenvalues evaluated at these steady states are respectively $-\beta c < 0$, $a_1 > 0$, $a_3 > 0$ (steady state 1 is globally unstable) and $-\beta c < 0$, $a_1 + \frac{a_3 d_1}{b_3} > 0$, $-a_3 < 0$ (steady state 2 is a saddle point). As for steady state 3, characterized by the extinction of species 3, the eigenvalues are $-\beta c < 0$, $-a_1 + q_1 \frac{I}{c} < 0$, $a_3 - \frac{d_3}{b_1} (a_1 - q_1 \frac{I}{c}) > 0$ according to condition (9). Hence steady state 3 is also unstable. Finally, for steady state 4 the characteristic equation reads:

$$(-\beta c - \lambda) (\lambda^2 + (b_1 X_1^* + b_3 X_3^*) \lambda + (b_1 b_3 + d_1 d_3) X_1^* X_3^*) = 0$$

It admits 3 roots: $-\beta c < 0$ and are 2 other roots, either real and negative or complex with a negative real part, depending on the sign of the discriminant, that reads: $(b_1 X_1^* - b_3 X_3^*)^2 - 4d_1 d_3 X_1^* X_3^*$. Hence steady state 4 is asymptotically stable, and is a stable node in the first case, a stable focus in the second one.

B.3 Capture fishery and aquaculture: proof of Proposition 1, (ii)

The linearization of the dynamic system (30) in the neighborhood of the steady state yields the following Jacobian matrix:

$$J = \begin{pmatrix} \left. \frac{\partial F_1(X_1, X_3)}{\partial X_1} \right|_{\widehat{X}_1, \widehat{X}_3} - q_1 \widehat{E}_1 & -q_1 \widehat{X}_1 & \left. \frac{\partial F_1(X_1, X_3)}{\partial X_3} \right|_{\widehat{X}_1, \widehat{X}_3} & 0 \\ a_{21} & a_{22} - \beta c & -a_{23} & -a_{24} \\ \left. \frac{\partial F_3(X_1, X_3)}{\partial X_1} \right|_{\widehat{X}_1, \widehat{X}_3} & 0 & \left. \frac{\partial F_3(X_1, X_3)}{\partial X_3} \right|_{\widehat{X}_1, \widehat{X}_3} - q_3 \widehat{E}_3 & -q_3 \widehat{X}_3 \\ -a_{21} & -a_{22} & a_{23} & a_{24} - \beta c \end{pmatrix}$$

with

$$\begin{cases} a_{21} = \beta I \frac{\sigma-1}{\sigma} \frac{\widehat{A}(1-\widehat{A})}{\widehat{X}_1} \\ a_{22} = \beta I \frac{\sigma-1}{\sigma} \frac{\widehat{A}(1-\widehat{A})}{\widehat{E}_1} = \beta c \frac{\sigma-1}{\sigma} \widehat{A} \\ a_{23} = \beta I \frac{\sigma-1}{\sigma} \gamma \frac{\widehat{A}(1-\widehat{A})}{\widehat{X}_3} \\ a_{24} = \beta I \frac{\sigma-1}{\sigma} \gamma \frac{\widehat{A}(1-\widehat{A})}{\widehat{E}_3} = \beta c \frac{\sigma-1}{\sigma} (1 - \widehat{A}) \end{cases}$$

and

$$\begin{aligned}
\frac{\partial F_1(X_1, X_3)}{\partial X_1} \Big|_{\widehat{X}_1, \widehat{X}_3} - q_1 \widehat{E}_1 &= \frac{\partial F_1(X_1, X_3)}{\partial X_1} \Big|_{\widehat{X}_1, \widehat{X}_3} - \frac{F_1(\widehat{X}_1, \widehat{X}_3)}{\widehat{X}_1} = -b_1 \widehat{X}_1 \\
\frac{\partial F_1(X_1, X_3)}{\partial X_3} \Big|_{\widehat{X}_1, \widehat{X}_3} &= d_1 \widehat{X}_1 \\
\frac{\partial F_3(X_1, X_3)}{\partial X_1} \Big|_{\widehat{X}_1, \widehat{X}_3} &= -d_3 \widehat{X}_3 \\
\frac{\partial F_3(X_1, X_3)}{\partial X_3} \Big|_{\widehat{X}_1, \widehat{X}_3} - q_3 \widehat{E}_3 &= \frac{\partial F_3(X_1, X_3)}{\partial X_3} \Big|_{\widehat{X}_1, \widehat{X}_3} - \frac{F_3(\widehat{X}_1, \widehat{X}_3)}{\widehat{X}_3} = -b_3 \widehat{X}_3
\end{aligned}$$

Tedious computations show that the characteristic polynomial reads:

$$P(\lambda) = (\beta c + \lambda) Q(\lambda)$$

with

$$Q(\lambda) = \mu_3 \lambda^3 + \mu_2 \lambda^2 + \mu_1 \lambda + \mu_0$$

and

$$\begin{cases}
\mu_3 = 1 \\
\mu_2 = \frac{\beta c}{\sigma} + b_1 \widehat{X}_1 + b_3 \widehat{X}_3 \\
\mu_1 = \frac{\beta c}{\sigma} (b_1 \widehat{X}_1 + b_3 \widehat{X}_3) + (b_1 b_3 + d_1 d_3) \widehat{X}_1 \widehat{X}_3 + \frac{\sigma-1}{\sigma} \beta I \widehat{A} (1 - \widehat{A}) (q_1 + \gamma q_3) \\
\mu_0 = \frac{\beta c}{\sigma} (b_1 b_3 + d_1 d_3) \widehat{X}_1 \widehat{X}_3 + \frac{\sigma-1}{\sigma} \beta I \widehat{A} (1 - \widehat{A}) (b_1 \gamma q_3 \widehat{X}_1 + b_3 q_1 \widehat{X}_3 + d_3 \gamma q_1 \widehat{X}_1 - d_1 q_3 \widehat{X}_3)
\end{cases}$$

$P(\lambda)$ admits one negative real root equal to $-\beta c$, plus the 3 roots of $Q(\lambda)$. We apply the Routh-Hurwitz criterion to $Q(\lambda)$. Clearly, $\mu_3 > 0$, $\mu_2 > 0$ and $\mu_1 > 0$. The sign of μ_0 is ambiguous. Besides, the sign of $\mu_2 \mu_1 - \mu_3 \mu_0$ is also ambiguous:

$$\begin{aligned}
\mu_2 \mu_1 - \mu_3 \mu_0 &= \left(\frac{\beta c}{\sigma} + b_1 \widehat{X}_1 + b_3 \widehat{X}_3 \right) \left(\frac{\beta c}{\sigma} (b_1 \widehat{X}_1 + b_3 \widehat{X}_3) + (b_1 b_3 + d_1 d_3) \widehat{X}_1 \widehat{X}_3 + \frac{\sigma-1}{\sigma} \beta I \widehat{A} (1 - \widehat{A}) (q_1 + \gamma q_3) \right) \\
&\quad - \frac{\beta c}{\sigma} (b_1 b_3 + d_1 d_3) \widehat{X}_1 \widehat{X}_3 - \frac{\sigma-1}{\sigma} \beta I \widehat{A} (1 - \widehat{A}) (b_1 \gamma q_3 \widehat{X}_1 + b_3 q_1 \widehat{X}_3 + d_3 \gamma q_1 \widehat{X}_1 - d_1 q_3 \widehat{X}_3) \\
&= (b_1 \widehat{X}_1 + b_3 \widehat{X}_3) \left[\left(\frac{\beta c}{\sigma} \right)^2 + \frac{\beta c}{\sigma} (b_1 \widehat{X}_1 + b_3 \widehat{X}_3) + (b_1 b_3 + d_1 d_3) \widehat{X}_1 \widehat{X}_3 \right] \\
&\quad + \frac{\sigma-1}{\sigma} \beta I \widehat{A} (1 - \widehat{A}) \left[\frac{\beta c}{\sigma} (q_1 + \gamma q_3) + q_1 (b_1 - \gamma d_3) \widehat{X}_1 + q_3 (d_1 + \gamma b_3) \widehat{X}_3 \right]
\end{aligned}$$

Nevertheless, we can obtain the following results.

- Absent biological interactions ($d_1 = d_3 = 0$) we have $\mu_0 > 0$ and $\mu_2\mu_1 - \mu_3\mu_0 > 0$. In this case, the linearized dynamic system is stable (see Gantmacher, 1959). This remains true as long as biological interactions are not too strong. More precisely, a sufficient condition for $\mu_0 > 0$ is $d_1 \leq b_3 \frac{q_1}{q_3}$, and a sufficient condition for $\mu_2\mu_1 - \mu_3\mu_0 > 0$ is $d_3 \leq \frac{b_1}{\gamma}$.
- When the revenue spent on fish I tends to 0, $\widehat{X}_1 \rightarrow \widetilde{X}_1$, $\widehat{X}_3 \rightarrow \widetilde{X}_3$, $\mu_0 \rightarrow \frac{\beta c}{\sigma} (b_1 b_3 + d_1 d_3) \widetilde{X}_1 \widetilde{X}_3 > 0$ and $\mu_2\mu_1 - \mu_3\mu_0 \rightarrow (b_1 \widetilde{X}_1 + b_3 \widetilde{X}_3) \left[\left(\frac{\beta c}{\sigma} \right)^2 + \frac{\beta c}{\sigma} (b_1 \widetilde{X}_1 + b_3 \widetilde{X}_3) + (b_1 b_3 + d_1 d_3) \widetilde{X}_1 \widetilde{X}_3 \right] > 0$ and the system is stable.

C Proof of Proposition 2

(i) Eliminating \widehat{A} between equations (32) and (34) yields a relationship between the two long run effort levels:

$$\widehat{E}_1 + \frac{\widehat{E}_3}{\gamma} = \frac{I}{c}$$

Remember that absent aquaculture the optimal level of effort in the capture fishery is $E_1^* = I/c$. Then obviously $\widehat{E}_1 + \widehat{E}_3 < E_1^*$.

(ii) Now, comparing \widehat{X}_1 (equation (31)) to the stock of the baseline case without aquaculture X_1^* (equation (16)), we get:

$$\widehat{X}_1 = X_1^* + \frac{b_3}{b_1 b_3 + d_1 d_3} y_1 \widehat{A}$$

Hence

$$\widehat{X}_1 > X_1^* \iff y_1 > 0 \iff d_1 < \bar{d}_1 = b_3 \frac{q_1}{\gamma q_3}$$

The steady state expressions of the wild edible fish price are $P_1^* = c/(q_1 X_1^*)$ and $\widehat{P}_1 = c/(q_1 \widehat{X}_1)$, hence the result. Concerning the wild feed fish stock, comparing \widehat{X}_3 (equation (33)) and X_3^* (equation (17)) yields:

$$\widehat{X}_3 = X_3^* - \frac{d_3}{b_1 b_3 + d_1 d_3} y_3 \widehat{A} < X_3^* \quad \text{since } d_3 > 0 \text{ and } y_3 > 0$$

(iii) When aquaculture lowers the wild edible fish stock ($d_1 > \bar{d}_1$), as $\widehat{E}_1 < E_1^*$, the supply of wild edible fish is necessarily lower: $\widehat{Y}_1 < Y_1^*$. It may even be the case that the introduction of

aquaculture causes the collapse of the wild fish stock in the long run: when $\bar{I} < I < I_w(d_1)$ and no interior steady state exists or there exist two unstable interior steady state, the wild fishery alone would have been sustainable.

Now, when aquaculture leads to an increased wild edible stock ($d_1 < \bar{d}_1$), its impact on wild fish supply is ambiguous, except in the particular case where the introduction of aquaculture prevents the edible fish stock from collapsing, that is when $I_w(d_1) < I < \bar{I}$. Likewise, when aquaculture increases wild fish supply, it obviously increases also total fish supply, whereas when aquaculture decreases wild fish supply the net effect of aquaculture on total fish supply is ambiguous.

(iv) Turning to the comparison of utilities, we obtain:

$$\begin{aligned} \left(\frac{U(\hat{Y}_1, \hat{Y}_2)}{U(Y_1^*, 0)} \right)^{1-\frac{1}{\sigma}} &= \left(\frac{\hat{Y}_1}{Y_1^*} \right)^{1-\frac{1}{\sigma}} \left(1 + \frac{\alpha(k)}{1-\alpha(k)} \left(\frac{\hat{Y}_2}{\hat{Y}_1} \right)^{1-\frac{1}{\sigma}} \right) \\ &= \left(\frac{\hat{Y}_1}{Y_1^*} \right)^{1-\frac{1}{\sigma}} \frac{1}{1-\hat{A}} = \left(\frac{\hat{E}_1 \hat{X}_1}{E_1^* X_1^*} \right)^{1-\frac{1}{\sigma}} \frac{1}{1-\hat{A}} = \left(\frac{\hat{X}_1}{X_1^*} \right)^{1-\frac{1}{\sigma}} (1-\hat{A})^{-\frac{1}{\sigma}} \\ U(\hat{Y}_1, \hat{Y}_2) > U(Y_1^*, 0) &\iff \left(\frac{\hat{X}_1}{X_1^*} \right)^{1-\frac{1}{\sigma}} > (1-\hat{A})^{\frac{1}{\sigma}} \iff \frac{\hat{X}_1}{X_1^*} > (1-\hat{A})^{\frac{1}{\sigma-1}} \end{aligned}$$

This condition is always satisfied when $\hat{X}_1 \geq X_1^*$ i.e. when $d_1 \leq \bar{d}_1$, which is a sufficient condition for aquaculture to increase welfare. We exhibit numerically a case where the introduction of aquaculture leads to a decrease of utility.

D Proof of Propositions 3 and 4

D.1 Proof of Proposition 3

From system (31)–(34) (with $d_1 = d_3 = 0$) we get for stocks and efforts:

$$\begin{aligned} d\hat{X}_1 &= \frac{q_1}{b_1} \frac{I}{c} d\hat{A}, & d\hat{E}_1 &= -\frac{I}{c} d\hat{A} \\ d\hat{X}_3 &= -\frac{\gamma q_3}{b_3} \frac{I}{c} d\hat{A}, & d\hat{E}_3 &= \gamma \frac{I}{c} d\hat{A} \end{aligned}$$

Hence $d\hat{X}_1$ and $d\hat{X}_3$ are always of opposite signs, as well as $d\hat{E}_1$ and $d\hat{E}_3$.

As for catches and prices, we obtain:

$$\begin{aligned}\frac{d\widehat{Y}_1}{\widehat{Y}_1} &= \frac{d\widehat{E}_1}{\widehat{E}_1} + \frac{d\widehat{X}_1}{\widehat{X}_1} = \left(\frac{a_1/b_1}{\widehat{X}_1} - 2 \right) \frac{d\widehat{A}}{1-\widehat{A}}, & \frac{d\widehat{P}_1}{\widehat{P}_1} &= -\frac{d\widehat{A}}{1-\widehat{A}} - \frac{d\widehat{Y}_1}{\widehat{Y}_1} = \left(1 - \frac{a_1/b_1}{\widehat{X}_1} \right) \frac{d\widehat{A}}{1-\widehat{A}} \\ \frac{d\widehat{Y}_3}{\widehat{Y}_3} &= \frac{d\widehat{E}_3}{\widehat{E}_3} + \frac{d\widehat{X}_3}{\widehat{X}_3} = \left(2 - \frac{a_3/b_3}{\widehat{X}_3} \right) \frac{d\widehat{A}}{\widehat{A}}, & \frac{d\widehat{P}_3}{\widehat{P}_3} &= \frac{d\widehat{A}}{\widehat{A}} - \frac{d\widehat{Y}_3}{\widehat{Y}_3} = \left(\frac{a_3/b_3}{\widehat{X}_3} - 1 \right) \frac{d\widehat{A}}{\widehat{A}} \\ \frac{d\widehat{Y}_2}{\widehat{Y}_2} &= \frac{dk}{k} + \gamma \frac{d\widehat{Y}_3}{\widehat{Y}_3}, & \frac{d\widehat{P}_2}{\widehat{P}_2} &= \frac{d\widehat{A}}{\widehat{A}} - \frac{d\widehat{Y}_2}{\widehat{Y}_2}\end{aligned}$$

Absent biological interactions, a_1/b_1 (resp. a_3/b_3) is the carrying capacity of species 1 (resp. species 3). We thus have $1 - \frac{a_1/b_1}{\widehat{X}_1} < 0$ and $\frac{a_3/b_3}{\widehat{X}_3} - 1 > 0$: $d\widehat{P}_1$ and $d\widehat{P}_3$ are always of opposite signs. For catches, things depend on the initial value of the stock with respect to half its carrying capacity. This proves (i).

We have expressed so far how our variables evolve according to a variation of \widehat{A} , the market interaction variable. We must now determine how \widehat{A} itself evolves according to a variation of k , the efficiency of aquaculture.

Equation (35) defining \widehat{A} can be written as:

$$\frac{\widehat{A}}{1-\widehat{A}} = \frac{\alpha}{1-\alpha} \left(\frac{\widehat{Y}_2}{\widehat{Y}_1} \right)^{\frac{\sigma-1}{\sigma}}$$

Totally differentiating this equation, we obtain:

$$\frac{d\widehat{A}}{\widehat{A}(1-\widehat{A})} = \frac{\sigma-1}{\sigma} \left[\frac{d\widehat{Y}_2}{\widehat{Y}_2} - \frac{d\widehat{Y}_1}{\widehat{Y}_1} \right]$$

from which we deduce:

$$\frac{d\widehat{Y}_2}{\widehat{Y}_2} = \frac{d\widehat{A}}{\widehat{A}(1-\widehat{A})} + \frac{\sigma}{\sigma-1} \frac{d\widehat{Y}_1}{\widehat{Y}_1}$$

As we have shown above that for $\widehat{X}_1 \leq \frac{a_1/b_1}{2}$, $d\widehat{Y}_1$ and $d\widehat{A}$ have the same sign, this equation shows that it is also the case for $d\widehat{Y}_2$.

Finally, we can deduce from this equation, by replacing $d\widehat{Y}_1$ and $d\widehat{Y}_2$ by their expression as a function of $d\widehat{A}$, that:

$$\left[\frac{1}{1-\widehat{A}} - \frac{\sigma-1}{\sigma} \left(\gamma \left(2 - \frac{a_3/b_3}{\widehat{X}_3} \right) + \frac{\widehat{A}}{1-\widehat{A}} \left(2 - \frac{a_1/b_1}{\widehat{X}_1} \right) \right) \right] \frac{d\widehat{A}}{\widehat{A}} = \frac{\sigma-1}{\sigma} \frac{dk}{k}$$

For $\widehat{X}_1 \leq \frac{a_1/b_1}{2}$ and $\widehat{X}_3 \leq \frac{a_3/b_3}{2}$, the term between brackets on the left-hand side of this equation is unambiguously positive. Then $d\widehat{A}/dk > 0$. It immediately follows that:

$$\begin{aligned} \frac{d\widehat{X}_1}{dk} &> 0, & \frac{d\widehat{E}_1}{dk} &< 0, & \frac{d\widehat{X}_3}{dk} &< 0, & \frac{d\widehat{E}_3}{dk} &> 0 \\ \frac{d\widehat{Y}_1}{dk} &> 0, & \frac{d\widehat{P}_1}{dk} &< 0, & \frac{d\widehat{Y}_3}{dk} &< 0, & \frac{d\widehat{P}_3}{dk} &> 0 \\ \frac{d\widehat{Y}_2}{dk} &> 0, & \frac{d\widehat{P}_2}{dk} &< 0 & & & & \end{aligned}$$

This proves (ii).

D.2 Proof of Proposition 4

When preferences depend on k , either through the weight α of farmed fish in utility or through the elasticity of substitution σ between wild and farmed fish, the previous equation becomes:

$$\left[\frac{1}{1-\widehat{A}} - \frac{\sigma-1}{\sigma} \left(\gamma \left(2 - \frac{a_3/b_3}{\widehat{X}_3} \right) + \frac{\widehat{A}}{1-\widehat{A}} \left(2 - \frac{a_1/b_1}{\widehat{X}_1} \right) \right) \right] \frac{d\widehat{A}}{\widehat{A}} = \left[1 - \frac{1}{\sigma(k)} \left(1 - \frac{k\sigma'(k)}{\sigma(k)} \right) + \frac{k\alpha'(k)}{\alpha(k)(1-\alpha(k))} \right]$$

As $\alpha'(k) < 0$ and $\sigma'(k) < 0$, it may be the case that the right-hand side of the above equation is negative. More precisely, there may exist a threshold for the parameter k above which $d\widehat{A}/dk$ changes sign.