Consumer preferences, aquaculture technology and the sustainability of fisheries

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December 18, 2012

Abstract

This article analyzes the impact of aquaculture on wild fish stocks and on fish consumption, taking into account two key components: (1) its dependence on reduction fisheries for the feeding of the farmed species; (2) consumer preferences. The model includes the demand side and three sectors: an edible fish fishery and a reduction fishery, both in open access, and an aquaculture sector. Focusing on the demand arising from wealthy populations, we assume consumer preferences are carnivorous species biased. On the other hand, the productivity of the aquaculture sector depends on the diet of the farmed species. We show that consumers are better-off in presence of aquaculture. Indeed, aquaculture increases global fish supply, which in turn, alleviates pressure on the long run edible stock through decreased fish price. Furthermore, the income level for which collapse of the wild edible fishery occurs is postponed. However, the choice of the farmed species entails a trade-off between the edible fishery and the reduction fishery which stems from the characteristics of the demand side. Therefore, we explore the consequences of the sensitivity of consumers to the farmed fish type. We also analyze the dynamics of fish stocks, supplies and prices and find that accounting for the demand side leads to a stable equilibrium whether the aquaculture sector is included to the model or not.

Keywords: edible fishery, aquaculture, reduction fishery, carnivorous preferences.

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 halieutic resources.

Aquaculture exists in many parts of the world since the Middle Age 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 (2010), at date, about 50% of world marine fish stocks are estimated as fully exploited and 32% are 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.

Since the early 1970s the aquaculture sector has been the fastest growing food industry, with an annual average growth of 8.3% over the 1970-2008 period (FAO, 2010). In 2000 aquaculture represented 27% of world fish production, while in 2009 this figure shifted to 38% (FAO, 2010). Focusing on production for human consumption, aquaculture has nearly doubled this quantity in recent years. The FAO Food Outlook (2011) reports that in 2010, capture fisheries managed to provide 9 kg of food fish per capita, per year, versus 8.6 kg for aquaculture. In fact, aquaculture is increasingly viewed as a source of food safety. 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 and prosperity. Aquaculture's main inputs are: land, water, labor, feed and seed. The degree of use of these inputs depends on the attributes of a production system (whether it is extensive, semi-intensive or intensive), and on the species bred. In any event, inland and costal farms cause the destruction of natural habitats, eroding biodiversity. In addition, the release of untreated water, food and faeces damages wild ecosystems, in particular through pathogene invasions. When fertilizers are added in the fish diet, wastes contain nitrogen, phosphorus and other substances inducing eutrophication[1]. Regarding seeds, they are still sourced from the wild for the culture of many species, rather than derived from hatcheries, occasioning disastrous effects on natural populations (Naylor *et al.*, 2000, FAO, 2011). Finally, aquaculture also depends on natural populations for feeding of carnivorous species and, to a lesser extent, of omnivorous and

[1]Eutrophication 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.

certain herbivorous species. Fishmeal and fish oil, which compose feed for these species, are made from small oily fishes belonging to low trophic levels[2] for about 80% and wastes from processed fish for 20% (Fishmeal Information Network, 2011).

The demand for fishmeal and fish oil participates to the fishing pressure drilled on wild stocks. At date, reduction fisheries are described as fully exploited or over-exploited (Grainger and Garcia, 1996; Alder *et al.* 2008). Aquaculture is the world's largest user of fishmeal and fish oil. In 2009 it consumed 53% of fishmeal and 81% of fish oil world production (IFFO, 2011). The sector has succeeded in maintaining a high growth rate in spite of the static landings of feed fish thanks to important progress in terms of rationalization of fishmeal inputs (Bjorndal and Asche, 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.

Several studies ask about the degree of substitutability between fishmeal and plant-based food. Soyameal emerged as a great candidate. It possesses most of the characteristics allowing high fish quality. However, Kristofersson and Anderson (2006) shows that both types of proteins are not highly substitutable. According to Shamshak and Anderson (2008) beyond some degree of replacement of fishmeal by plant-based food, certain farmed species are subject to declines in health, growth rate and omega 3 levels due to the lower protein quality and content. Single cell proteins or zooplankton are considered as potential substitutes to fishmeal protein though production costs remain too high to be used in significant amounts in aquaculture feed (Olsen and Hasan, 2012). At the moment, it does not seem to exist a protein source displaying required properties and profitable at the same time.

This article analyzes the impact of aquaculture on fish consumption and on wild fish stocks via its contribution to food fish production, and accounting for its dependence on wild input.

A few studies have investigated the market and biological interactions between aquaculture and capture fisheries. Anderson (1985) shows that in a situation of low production of a capture fishery in open access and therefore, high price, the entry of aquaculture increases total fish supply, and the wild fish stock through a lower consumer price. Beddington and Ye (1996) also tackles the market interactions between wild and farmed fish, but assumes both goods are imperfect substitutes with positive cross-price elasticities. Similarly, the authors find positive social benefits of aquaculture

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

via increased fish supply and reduced prices. Yet, the extent of aquaculture production impact is lower than when the two goods are perfect substitutes. Hannesson (2002) considers both market and biological interactions. He introduces an edible fish which is harvested or farmed and a feed fish stock. The wild edible fish feeds on feed fish, while the aquaculture sector harvests feed fish to grow farmed edible fish. 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.

Our model consists of the demand side and three sectors: an edible fish fishery, a reduction fishery and an aquaculture sector. Both fisheries are in open access. As in Hannesson (2002), we tackle the dependence of aquaculture on fish feeds by including a feed fish stock on which the aquaculture production relies. Though, we assume the wild fish designed to human consumption does not feed on the feed fish stock, ignoring the potential biological interaction existing between the two sectors.

The novelty of our approach lies in the modeling of the relationship between consumer preferences and the production technology of aquaculture. Edible wild fish and farmed fish are strong substitutes. The taste for the farmed fish depends on its diet: the more carnivorous the farmed species is, the more consumers like it[3]. But the breeding of carnivorous species is inefficient, in the sense that the production of 1kg of flesh requires more than 1kg of wild feed fish. At the opposite, omnivorous and herbivorous species, which are little valued by consumers, are more environmental friendly, in the sense that their production uses small quantities of wild fish input to none at all.

We derive steady state outcomes from our model as well as the short run adjustments of prices, stock levels and supplies of each commodity to appraise the dynamics resulting of the interactions between the aquaculture and capture fisheries sectors. We show that consumers are better-off in presence of aquaculture. Indeed, aquaculture increases global fish supply, which in turn, alleviates pressure on the long run edible stock through decreased fish price. Furthermore, the income level for which collapse of the wild edible fishery occurs is postponed. However, the choice of the farmed species entails a trade-off between the edible fishery and the reduction fishery which stems from the characteristics of the demand side. Therefore, we explore the consequences of the sensitivity of consumers to the farmed fish type. We also analyze the dynamics of fish stocks, supplies and prices and find that accounting for the demand side leads to a stable equilibrium whether the

[3] Worldwide, carnivorous species such as grouper, cod-fish, halibut, sole etc. display higher economic values that omnivorous ones (FranceAgriMer, 2012; ADF&G, 2010).

aquaculture sector is included to the model or not.

The remaining of the paper is as follows. Section 2 presents the demand side features. Section 3 describes the short run dynamics and the long run state of the fishery harvesting edible fish in open access, in absence of the aquaculture sector. This constitutes our baseline situation for appraising the impact of the aquaculture activity. In Section 4 we introduce aquaculture and the coupling of the different sectors. We analyze the associated steady state and compare it to the one of the baseline situation. We finally study the role of consumer tastes. Section 5 presents numerical simulations. Section 6 concludes.

2 The demand side

Consumers purchase two types of goods: wild fish and farmed fish. They are assumed to be indifferent to whether a fish is farmed or wild caught. What is considered determinant is a species type and flesh quality.

The utility function of the representative consumer at each date t is given by:

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

with Y_1 the wild fish and Y_2 the farmed one. In a world with two fish products it is reasonable to assume that they are strong substitutes. Obviously, if they displayed a certain degree of complementarity we would have not consumed wild fish at the time aquaculture did not exist. Hence, the elasticity of substitution, σ, is greater than 1.

We consider that the wild fish product is a highly valued carnivorous species. On the other hand, the taste for the farmed fish is increasing in its feed fish dietary requirements. Such attribute is traduced by the parameter $k \in]0; k_{max}]$. The parameter k also intervenes in the production function of the aquaculture sector as it conveys the sector's efficiency in transforming 1 kg of low-value fish into a high-value species (see (15)). It can also be interpreted as the farmed species' diet. When k is high the quantity of feed fish required to produce farmed fish is relatively low. This implies the species farmed is rather omnivorous or herbivorous. When k is low farmed fish is rather a carnivorous species, requiring a large quantity of feed fish to produce flesh.

The function $\alpha(k)$ weights preferences of consumers for each type of good. It is decreasing in k, and belongs to $[\alpha_{\min}; 0.5]$. That is, consumers have a preference for carnivorous species. Furthermore, we assume that the farmed fish can be weighted by consumers as much as the wild fish, but not more. Facts and literature are not unanimous on the behavior of consumers regarding wild versus farmed products[4]. However, we make the assumption that the wild product is more valued to reflect the fact that aquaculture may 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, 2012). In addition, there exists some empirical evidence of higher wild product prices than farmed at equal species (FranceAgriMer, 2012).

The budget constraint of the consumer is:

$$P_{1t}Y_{1t} + P_{2t}Y_{2t} = I_t \tag{2}$$

where I_t is the representative consumer's total expenditures on fish consumption at date t, exogenous, 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:

$$Y_{1t}^d = \frac{I_t}{P_{1t}\left[1 + a(k)\left(\frac{P_{1t}}{P_{2t}}\right)^{\sigma-1}\right]} \tag{3}$$

$$Y_{2t}^d = \frac{I_t}{P_{2t}\left[1 + \frac{1}{a(k)}\left(\frac{P_{2t}}{P_{1t}}\right)^{\sigma-1}\right]} \tag{4}$$

with

$$a(k) = \left(\frac{\alpha(k)}{1-\alpha(k)}\right)^{\sigma} \tag{5}$$

$a(k)$ is an increasing function of $\alpha(k)$, hence a decreasing function of k.remember that the lower k is the more consumers like farmed fish.

As it is well known when preferences are represented by a CES utility function, the response of Y_1 (resp. Y_2) to a variation of P_2 (resp. P_1) depends on the value of the elasticity of substitution.

[4]For instance, regarding salmon, Knapp *et al.* (2007) argues that species of fish equal, consumers tend to prefer the farmed product for its consistent quality, the reliability of its supply and its more appealing aspect.

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 The baseline situation: capture fishery alone

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

$$Y_{1t}^d = \frac{I_t}{P_{1t}} \tag{6}$$

and the price elasticity of demand is unitary.

The dynamics of the capture fishery is described by the Schaefer (1954) model:

$$\dot{X}_{1t} = F_1(X_{1t}) - Y_{1t} \tag{7}$$

$$F_1(X_{1t}) = r_1 X_{1t}\left(1 - \frac{X_{1t}}{K_1}\right) \tag{8}$$

$$Y_{1t} = q_1 E_{1t} X_{1t} \tag{9}$$

X_{1t} is the stock level at time t, $F_1(X_{1t})$ represents to the species' biological growth, with K_1 the carrying capacity of the environment and r_1 the intrinsic growth rate of the species, Y_{1t} is the catch at time t, E_{1t} the level of fishing effort and q_1 the catchability coefficient. The fishermen's profit is written as follows:

$$\pi_{1t} = P_{1t} Y_{1t} - cE_{1t} \tag{10}$$

where c stands for the unit cost of effort.

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

$$\dot{E}_{1t} = \beta\pi_{1t} = \beta(q_1 P_{1t} X_{1t} - c)E_{1t}, \quad \beta > 0 \tag{11}$$

Textbooks (Clark, 1990 for instance) usually describe the short run dynamics of fish supply in open access for a given (constant) price P_1, ignoring demand or, equivalently, making the assumption of an infinite price elasticity of demand. In such case, the dynamic system defining the wild fish supply is composed of the two dynamic equations (7) and (11), taking into account the fishery production function (9). Extinction of the wild species never occurs, but overexploitation is of course possible, in the sense that the long run stock may be lower than $K_1/2$. As the fish price cannot adjust according to supply volumes, when low catches make the activity become unprofitable, fishermen exit the fishery. These capacity adjustments allow the stock to maintain a (possibly very low) positive level. The long term supply of wild fish as a function of its price corresponds to the well known backward bending supply curve described by Copes (1970) and Anderson (1973). In the neighborhood of the steady state, the system is globally stable. For any initial value of the control variable (effort in our case) below a certain level[5], 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. In this last case, trajectories are characterized by damped oscillations.

But the fish price has no reason to remain constant. The interplay between supply and demand on the fish market and the associated evolution of the price P_1 have to be taken into account.

We make the assumption that demand is stationary: $I_t = I \; \forall t$, and add to the previous dynamic system the equilibrium of the wild fish market at each date $Y_{1t} = Y_1^d(P_{1t})$, $Y_1^d(P_{1t})$ being given by (6). Eliminating P_1 and Y_1 yields the following two-dimensional dynamic system in X_{1t} and E_{1t} :

$$\begin{cases} \dot{X}_{1t} = F_1(X_{1t}) - q_1 E_{1t} X_{1t} \\ \dot{E}_{1t} = \beta \left(I - c E_{1t} \right) \end{cases} \tag{12}$$

The unique stationary stock and effort are:

$$X_1^* = \begin{cases} K_1 \left(1 - \frac{q_1 I}{r_1 c} \right) \text{ iff } \frac{q_1 I}{r_1 c} < 1 \\ 0 \text{ otherwise} \end{cases} \tag{13}$$

$$E_1^* = \begin{cases} \frac{I}{c} \text{ iff } \frac{q_1 I}{r_1 c} < 1 \\ 0 \text{ otherwise} \end{cases} \tag{14}$$

If $I \geq \frac{r_1 c}{q_1}$ the wild fish is doomed to extinction in the long run. Quite intuitively, this situation is likely to occur if the revenue spent by consumers on fish purchase is high, so as if the catchability

[5] Suppose 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 $E_{10} < 1/q_1$.

coefficient of the species is high, or if the unit cost of fishing and the intrinsic growth rate of the species are low.

It is easy to show that the steady state is a stable node. Contrary to the case where the elasticity of demand is infinite, paths describing damped oscillations are not possible here. The possibility for price to adjust plays a stabilizing role[6].

4 Introducing aquaculture

We now introduce the aquaculture sector, which exploits a distinct stock of small wild 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 consumer preferences on the long run status of both wild fish stocks.

4.1 The aquaculture sector and feed fishery

Farmers purchase fishmeal 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 are harvested from a stock of small fish of low economic value, X_3, distinct from the 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's 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:

$$Y_2 = kY_3{}^{\gamma} \tag{15}$$

[6] It may be noticed that effort evolves independently of the level of the stock. The dynamic equation for effort in (12) integrates into:

$$E_{1t} = E_1^* + (E_{10} - E_1^*)\, e^{-\beta ct}$$

The dynamic of effort is always monotonous. The convergence speed is βc.

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. k is the efficiency of the aquaculture sector which depends on the diet of the farmed species. Remember that it is the same parameter as in the consumer utility function.

Notice that Y_3/Y_2 corresponds 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. Both studies attest of substantial decrease in FIFO ratio since the 90's. Nonetheless, IFFO (2012) ratios' reflect greater achievements in terms of feed efficiencies. We will account for recent improvements of this ratio when calibrating our model in section 5.

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}). In the production function (15), γ is the share in value of feed input in the aquaculture output:

$$\gamma = \frac{P_{3t}Y_{3t}}{P_{2t}Y_{2t}} \tag{16}$$

As for the edible fishery, the feed fishery is described by the Schaeffer (1954) model, so that we have the equivalent of equations (7)–(9), subscript 1 being replaced by 3. It is also in open access, so that fishermen enter the sector until dissipation of the rent, and we have the equivalent of equation (11). The unit cost of fishing c is supposed to be the same in the two fishing sectors.

The fact that revenues from the aquaculture activity are directly proportional to the revenues of the feed industry (equation (16)) allows us to aggregate the aquaculture sector and the feed sector and to write the dynamic system representing the supply of farmed fish as:

$$\begin{cases} \dot{X}_{3t} = F_3(X_{3t}) - \left(\frac{Y_{2t}^s}{k}\right)^{\frac{1}{\gamma}} \\ \dot{E}_{3t} = \beta\left(\gamma P_{2t}Y_{2t}^s - cE_{3t}\right) \\ Y_{2t}^s = k\left(q_3 E_{3t} X_{3t}\right)^{\gamma} \end{cases} \tag{17}$$

This system of 4 variables, the supply of farmed fish Y_2, its price P_2, the effort E_3 exerted to obtain the feed and the stock of feed X_3, can be directly compared to the corresponding system for wild fish:

$$\begin{cases} \dot{X_{1t}} = F_1(X_{1t}) - Y_{1t}^s \\ \dot{E}_{1t} = \beta\left(P_{1t}Y_{1t}^s - cE_{1t}\right) \\ Y_{1t}^s = q_1 E_{1t} X_{1t} \end{cases} \tag{18}$$

Interactions between the two systems will come from demand, as we are going to show.

4.2 The coupling

We now introduce demands for both types of fish and the equilibria of the two fish markets.

Note

$$A_t = a(k)\left(\frac{P_{1t}}{P_{2t}}\right)^{\sigma-1} \tag{19}$$

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

$$P_{1t}Y_{1t}^d = \frac{I_t}{1+A_t} \tag{20}$$

$$P_{2t}Y_{2t}^d = \frac{A_t I_t}{1+A_t} \tag{21}$$

and the equilibria on the fish markets read:

$$P_{1t}q_1 E_{1t} X_{1t} = \frac{I_t}{1+A_t} \tag{22}$$

$$P_{2t}k\left(q_3 E_{3t} X_{3t}\right)^{\gamma} = \frac{A_t I_t}{1+A_t} \tag{23}$$

The ratio of equations (22) and (23) yields:

$$\frac{1}{A_t} = \frac{P_{1t}}{P_{2t}} \frac{q_1 E_{1t} X_{1t}}{k\left(q_3 E_{3t} X_{3t}\right)^{\gamma}}$$

Replacing the price ratio by its expression as a function of A given by (19) allows us to obtain:

$$A_t = a(k)^{\frac{1}{\sigma}}\left(\frac{k\left(q_3 E_{3t} X_{3t}\right)^{\gamma}}{q_1 E_{1t} X_{1t}}\right)^{\frac{\sigma-1}{\sigma}} \tag{24}$$

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 (17) and (18), using (20) and (21) to eliminate $P_{1t}Y_{1t}$ and $P_{2t}Y_{2t}$, and adding (24):

$$\begin{cases} \dot{X}_{1t} = F_1(X_{1t}) - q_1 E_{1t} X_{1t} \\ \dot{E}_{1t} = \beta \left[\frac{I}{1+A_t} - cE_{1t} \right] \\ \dot{X}_{3t} = F_3(X_{3t}) - q_3 E_{3t} X_{3t} \\ \dot{E}_{3t} = \beta \left[\gamma \frac{A_t I}{1+A_t} - cE_{3t} \right] \\ A_t = a(k)^{\frac{1}{\sigma}} \left(\frac{k(q_3 E_{3t} X_{3t})^{\gamma}}{q_1 E_{1t} X_{1t}} \right)^{\frac{\sigma-1}{\sigma}} \end{cases} \tag{25}$$

The steady state 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:

$$\widehat{X}_1 = K_1 \left(1 - \frac{q_1 I}{r_1 c} \frac{1}{1+\widehat{A}} \right) \tag{26}$$

$$\widehat{E}_1 = \frac{I}{c} \frac{1}{1+\widehat{A}} \tag{27}$$

$$\widehat{X}_3 = K_3 \left(1 - \gamma \frac{q_3 I}{r_3 c} \frac{\widehat{A}}{1+\widehat{A}} \right) \tag{28}$$

$$\widehat{E}_3 = \gamma \frac{I}{c} \frac{\widehat{A}}{1+\widehat{A}} \tag{29}$$

$$\widehat{A} = a(k)^{\frac{1}{\sigma}} \left(\frac{k \left(q_3 \widehat{E}_3 \widehat{X}_3 \right)^{\gamma}}{q_1 \widehat{E}_1 \widehat{X}_1} \right)^{\frac{\sigma-1}{\sigma}} \tag{30}$$

Proposition 1 *The condition of existence of an interior steady state where wild fishing and aquaculture coexist is:*

$$I < \frac{r_1 c}{q_1} + \frac{1}{\gamma} \frac{r_3 c}{q_3} \tag{31}$$

Moreover, under condition (31),the steady state is unique and globally stable.

Proof. From equations (26) and (28) we obtain the condition of coexistence of aquaculture and the edible fish fishery. We have:

$$\widehat{X}_1 > 0 \Longleftrightarrow I < \frac{r_1 c}{q_1}(1+\widehat{A})$$
$$\widehat{X}_3 > 0 \Longleftrightarrow I < \frac{1}{\gamma}\frac{r_3 c}{q_3}\frac{1+\widehat{A}}{\widehat{A}}$$

These conditions are both satisfied iff:

$$1 - \frac{r_1 c}{q_1 I} < \frac{\widehat{A}}{1+\widehat{A}} < \frac{1}{\gamma}\frac{r_3 c}{q_3 I}$$

We conclude that a necessary condition of existence of an interior solution is:

$$1 - \frac{r_1 c}{q_1 I} < \frac{r_3 c}{q_3 I} \Longleftrightarrow I < \frac{r_1 c}{q_1} + \frac{1}{\gamma}\frac{r_3 c}{q_3}$$

We show in Appendix A that under condition (31) the interior steady state exists (the condition is also sufficient) and is unique, and in Appendix B that it is globally stable. ■

We deduce three cases from Proposition 1:

1. $0 < I < r_1 c/q_1$: the wild edible fishery alone is sustainable, in the sense that it does not collapse in the long run, and the wild edible fishery and aquaculture may coexist and be sustainable;

2. $r_1 c/q_1 \leq I < r_1 c/q_1 + (1/\gamma)(r_3 c/q_3)$: the wild fishery alone collapses in the long run, but the wild edible fishery and aquaculture may coexist and be sustainable;

3. $r_1 c/q_1 + (1/\gamma)(r_3 c/q_3) \leq I$: neither the wild edible fishery alone nor the wild edible fishery plus aquaculture is sustainable.

In Case 3 consumers' expenditures on fish are so high that demand leads both fisheries to collapse. In Case 2, we see that in presence of aquaculture, the capture fishery can bear a higher income level. The income level for which the wild edible fish stock collapses is postponed. The maximum admissible income is the sum of the maximum admissible incomes for the existence in the long run of the capture fishery alone ($r_1 c/q_1$), and of aquaculture alone ($(1/\gamma) r_3 c/q_3$). Aquaculture, allowing the exploitation of non-edible wild fish and its transformation into edible farmed fish does represent a source of food safety.

We suppose that we are in Case 1 in the baseline situation: the edible fishery alone is sustainable. We wonder if the introduction of aquaculture represents an improvement on this situation, for consumers and also for the wild fish stocks.

4.3 Comparison with the baseline situation

The following proposition compares the steady state outcomes obtained in the baseline situation (equations (13) and (14)) to those obtained when the wild edible fishery and aquaculture coexist (equations (26)-(30)), under the condition of coexistence (31).

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;

(iii) an ambiguous effect on total wild fish stock;

(iv) an ambiguous effect on wild fish consumption;

(v) higher total fish consumption and consumer utility.

Proof. (i) Eliminating $\widehat{A}$ between equations (27) and (29) yields a relationship between the two long run effort levels:

$$\widehat{E}_1 + \frac{\widehat{E}_3}{\gamma} = \frac{I}{c} \tag{32}$$

Remember that absent aquaculture the optimal level of effort in the capture fishery is $E_1^* = I/c$. Equation (32) implies that $\widehat{E}_1 + \widehat{E}_3 < E_1^*$.

(ii) Now, comparing $\widehat{X}_1$ (equation (26)) to the stock of the baseline case without aquaculture X_1^* (equation (13)), it immediately appears that the stationary stock is higher with aquaculture than without, whatever $k > 0$. Which means, even an herbivorous species as a substitute would improve the status of the wild edible fish stock. As $\widehat{X}_1 > X_1^*$, the wild edible fish price is always lower in presence of aquaculture since the steady state expression of price is: $\widehat{P}_1 = c/(q_1\widehat{X}_1)$.

(iii) Turning to total wild fish stocks, absent aquaculture, the feed fish stock is unexploited and is at its carrying capacity K_3, hence the total wild fish stock is $X_1^* + K_3$. With aquaculture, it is equal to $\widehat{X}_1+\widehat{X}_3$. Using equations (13), (26) and (28) we obtain

$$\left(\widehat{X}_1+\widehat{X}_3\right) > (X_1^*+K_3) \Longleftrightarrow \gamma K_3\frac{q_3}{r_3} < K_1\frac{q_1}{r_1} \tag{33}$$

(iv) Concerning the supply of wild edible fish, simple computations show that:

$$\widehat{Y}_1 > Y_1^* \Leftrightarrow X_1^*+\widehat{X}_1 < K_1 \tag{34}$$

(v) Utility reads, with and without aquaculture,

$$U(\widehat{Y}_1,\widehat{Y}_2) = (1-\alpha(k))^{\frac{1}{1-\frac{1}{\sigma}}}\widehat{Y}_1\left[1+\frac{\alpha(k)}{1-\alpha(k)}\left(\frac{\widehat{Y}_2}{\widehat{Y}_1}\right)^{1-\frac{1}{\sigma}}\right]^{\frac{1}{1-\frac{1}{\sigma}}}$$

and

$$U(Y_1^*,0) = (1-\alpha(k))^{\frac{1}{1-\frac{1}{\sigma}}}Y_1^*$$

This yields, using (5) and the expressions of fish supply as functions of efforts and stocks:

$$\begin{aligned}\frac{U(\widehat{Y}_1,\widehat{Y}_2)}{U(Y_1^*,0)} &= \frac{\widehat{Y}_1}{Y_1^*}\left[1+\frac{\alpha(k)}{1-\alpha(k)}\left(\frac{\widehat{Y}_2}{\widehat{Y}_1}\right)^{1-\frac{1}{\sigma}}\right]^{\frac{1}{1-\frac{1}{\sigma}}}\\ &= \frac{q_1\widehat{E}_1\widehat{X}_1}{q_1E_1^*X_1^*}\left[1+a(k)^{\frac{1}{\sigma}}\left(\frac{k\left(q_3\widehat{E}_3\widehat{X}_3\right)^{\gamma}}{q_1\widehat{E}_1\widehat{X}_1}\right)^{1-\frac{1}{\sigma}}\right]^{\frac{1}{1-\frac{1}{\sigma}}}\end{aligned}$$

i.e., using (14), (13), (27), (26), and the definition of $\widehat{A}$ (30):

$$\frac{U(\widehat{Y}_1,\widehat{Y}_2)}{U(Y_1^*,0)} = \frac{1}{1+\widehat{A}}\,\frac{1-\frac{q_1 I}{r_1 c}\frac{1}{1+\widehat{A}}}{1-\frac{q_1 I}{r_1 c}}\left(1+\widehat{A}\right)^{\frac{1}{1-\frac{1}{\sigma}}} = \frac{1-\frac{q_1 I}{r_1 c}\frac{1}{1+\widehat{A}}}{1-\frac{q_1 I}{r_1 c}}\left(1+\widehat{A}\right)^{\frac{1}{\sigma-1}}$$

The right-hand side member of this equation is an increasing function of $\widehat{A}$, equal to 1 when $\widehat{A}=0$, which corresponds to the reference case without aquaculture. Therefore $U(\widehat{Y}_1,\widehat{Y}_2) > U(Y_1^*,0)$.

Finally, using the same equations, we immediatly get:

$$\frac{\widehat{Y}_1+\widehat{Y}_2}{Y_1^*} = \frac{\widehat{Y}_1}{Y_1^*}\left(1+\frac{\widehat{Y}_2}{\widehat{Y}_1}\right) = \frac{1-\frac{q_1 I}{r_1 c}\frac{1}{1+\widehat{A}}}{1-\frac{q_1 I}{r_1 c}}\,\frac{1+a(k)^{\frac{1}{\sigma-1}}\widehat{A}^{\frac{\sigma}{\sigma-1}}}{1+\widehat{A}}$$

Again, the right-hand side member of this equation is an increasing function of $\widehat{A}$, equal to 1 when $\widehat{A} = 0$. Therefore $\widehat{Y}_1 + \widehat{Y}_2 > Y_1^*$. ■

Proposition 2 calls for the following comments.

The total effective long run level of fishing effort is of course $\widehat{E}_1 + \widehat{E}_3$. Equation (32) indicates that there also exists a virtual total level of effort I/c, constant, which must be splitted into an effective effort $\widehat{E}_1$ devoted to catch the edible wild species, and a virtual effort $\widehat{E}_3/\gamma > \widehat{E}_3$ 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 (part (i) of the Proposition).

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 (part (ii) of the Proposition). However, the introduction of aquaculture, requiring the exploitation of low value fisheries that were not exploited before, has ambiguous effects on total wild fish stocks (part (iii)). According to equation (33), the introduction of aquaculture represents a "biological improvement", in the sense that the wild fish stock taken as a whole is higher with than without aquaculture, if the feed fish is not a very important input (γ low) and if the wild feed fish is more difficult to catch and reproduces more than the wild edible fish (q_3/r_3 low compared to q_1/r_1).

The introduction of aquaculture leads to a higher *total* fish consumption (part (v)), which is not surprising. Less intuitively, it may also lead to a higher *wild* fish consumption (part (vi)). According to condition (34), this happens when the edible fish stock is overexploited in the baseline situation ($X_1^* < K_1/2$), and when the introduction of aquaculture does not improve things too much ($\widehat{X}_1$ may be larger than $K_1/2$ but not too much).

Finally, the introduction of aquaculture is always beneficial for consumers (part (vi)), whatever their preferences and the efficiency of the aquaculture technology.

4.4 The role of consumer tastes

We study now the influence of k, the farmed species diet or the efficiency of the aquaculture sector, on the steady state variables, when wild fishery and aquaculture coexist. To do so, we perform a comparative statics exercise using system (26)–(30), in the neigborhood of a steady state where both stocks of wild fish are overexploited (see Appendix C). This case is the only one where we are able to obtain unambiguous analytical results, and is also the more empirically plausible.

Proposition 3 *(i) All long term variables in the edible fish sector and the feed fish sector systematically evolve in opposite way according to k.*

(ii) For $\widehat{X}_1 < K_1/2$ and $\widehat{X}_3 < K_3/2$ and when consumer preferences do not depend on k, which consequently represents simply the efficiency of aquaculture, the edible fish stock and catch rise with k at the expense of the feed fish stock and catch, while effort and price decrease in the first sector and increase in the second one. The effect of k on farmed fish production and price is ambiguous.

(iii) For $\widehat{X}_1 < K_1/2$ and $\widehat{X}_3 < K_3/2$ and when consumer preferences do depend on k, the effects are completely reversed if the dislike of consumers for herbivorous farmed fish is sufficiently high.

Proof. We show in Appendix C that:

$$\frac{d\widehat{X}_1}{d\widehat{A}} > 0, \quad \frac{d\widehat{E}_1}{d\widehat{A}} < 0, \quad \frac{d\widehat{Y}_1}{d\widehat{A}} > 0 \Leftrightarrow \widehat{X}_1 < \frac{K_1}{2}, \quad \frac{d\widehat{P}_1}{d\widehat{A}} < 0 \tag{35}$$

$$\frac{d\widehat{X}_3}{d\widehat{A}} < 0, \quad \frac{d\widehat{E}_3}{d\widehat{A}} > 0, \quad \frac{d\widehat{Y}_3}{d\widehat{A}} < 0 \Leftrightarrow \widehat{X}_3 < \frac{K_3}{2}, \quad \frac{d\widehat{P}_3}{d\widehat{A}} > 0 \tag{36}$$

$$\frac{d\widehat{Y}_2}{d\widehat{A}} = \widehat{Y}_2 \left(\frac{1}{k}\frac{dk}{d\widehat{A}} + \frac{\gamma}{\widehat{Y}_3}\frac{d\widehat{Y}_3}{d\widehat{A}} \right), \quad \frac{d\widehat{P}_2}{d\widehat{A}} = \widehat{P}_2 \left(\frac{1}{1+\widehat{A}} - \frac{1}{\widehat{Y}_2}\frac{d\widehat{Y}_2}{d\widehat{A}} \right) \tag{37}$$

which proves (i), and also that

$$\left[1 - \frac{\sigma-1}{\sigma}\frac{1}{1+\widehat{A}}\left(\gamma\left(2 - \frac{K_3}{\widehat{X}_3}\right) + \widehat{A}\left(2 - \frac{K_1}{\widehat{X}_1}\right)\right)\right]\frac{d\widehat{A}}{\widehat{A}} = \frac{1}{\sigma}\left(\frac{ka'(k)}{a(k)} + (\sigma-1)\right)\frac{dk}{k} \tag{38}$$

For $\widehat{X}_1 < K_1/2$ and $\widehat{X}_3 < K_3/2$, the term between brackets on the left-hand side member of equation (38) is unambiguously positive. When consumer preferences do not depend on k, $a'(k) = 0$ and the right-hand side member of equation (38) is also positive. Then we get $d\widehat{A}/dk > 0$. (ii) immediately follows.

When consumer preferences depend on k, the elasticity $-ka'(k)/a(k)$ may be lower or greater than $\sigma - 1$. It may now be the case that the right-hand side member of equation (38) is negative. Then $d\widehat{A}/dk < 0$. (iii) follows. ■

Absent any effect of k on consumer preferences, the more efficient the aquaculture sector (the higher k) the better the long term state of the edible fishery (the higher $\widehat{X}_1$), at the expense of the feed fishery (the lower $\widehat{X}_3$). The reason is that fishing feed fish becomes more and more attractive, as it can be transformed in more and more farmed fish, which is a strong substitute of wild edible fish. Notice that as a result, the higher is k, the better-off is the edible fishery relatively to the baseline situation, that is, the more distant are $\widehat{X}_1$ and X_1^*.

When consumer preferences depend on k, increasing k means not only having a more efficient aquaculture technology but also breeding fish that consumers like less. As k increases, the second effect pogressively dominates the first one. More precisely, since $\alpha(k)$ is monotonously decreasing, there may exist a threshold for the parameter k under which $d\widehat{A}/dk > 0$ and above which $d\widehat{A}/dk < 0$. Then, when the farmed species is very carnivorous and the wild fish stocks overexploited, increasing k i.e. choosing to breed a less carnivorous species is good for the edible fish stock, at the expense of the other stock. But increasing k too much reverses the process.

5 Numerical simulations

In this section we calibrate the model and solve it numerically. This allows us to simulate the transitional dynamics following the introduction of aquaculture, starting from the reference situation of an overexploited wild fishery at the steady state. We also investigate the sensitivity of the steady state outcomes to the model calibration, focusing on the parameter k, the diet of the farmed species.

5.1 The reference calibration

The reference calibration given in Table 1 is set such that absent aquaculture the edible fish stock is close to extinction at the steady state, while, in presence of aquaculture, steady state outcomes sketch the state of world resources, market prices and supplies, in relative values.

We use the following linear specification of the preference function:

$$\alpha(k) = 0.5 - (0.5 - \alpha_{\min})\frac{k}{k_{\max}}, \quad 0 < \alpha_{\min} < 0.5 \tag{39}$$

with α_{min} the minimum weight affected to the farmed fish Y_2 and k_{max} the maximum value of the parameter k.

Table 1: Calibration of the model.

K_1	r_1	q_1	I	c	β	σ	K_3	r_3	q_3	γ	k	α_{min}	k_{max}
100	0.36	0.052	10	1.58	0.05	2	400	0.68	0.43	0.46	1.9	0.1	7.5

K_1, K_3: 10^4 tons; r_1, r_3: years^{-1}; k: kg

The carrying capacities, K_1, K_3, are chosen as to obtain a realistic production ratio between a farmed and wild product in competition. The intrinsic growth rate r_1 is lower than r_3 as larger fish size are generally slower growing. The parameter k is set such that the farmed species is a high value carnivorous species. But as preferences are in favor of the wild product, Y_1, a lower weight is affected to Y_2: $\alpha(k) = 0.4$. The parameter γ gives feed costs equal to 46% 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. Income, I, is normalized to 10. It is the budget of the representative consumer for food fish consumption. As it is fictive, variables measured in currency such as product prices and the unit cost of effort are meaningless in absolute value. We will only interpret them in relative value.

5.1.1 The steady state outcomes

Table 2 gives the steady state outcomes in the baseline situation (absent aquaculture), applying the reference calibration.

Table 2: Baseline situation: steady state outcomes

X_1^*	E_1^*	P_1^*	Y_1^*	U^*
8.58†	6.33	3.54	2.82	1.02

$\dagger$ *in* 10^4 tons

The initial stock size is set equal to K_1. At the steady state X_1^* stands at 8.6% of the environment carrying capacity. The catch level equals 28,200 tons, though the Maximum Sustainable Yield[7] is worth 500,000 tons. By operating at a such low stock size, the fishery severely undermines its production potential.

[7] See Gordon, 1954.

Table 3 displays the long run results in presence of aquaculture.

Table 3: Situation with aquaculture: steady state outcomes

$\widehat{X}_1$	$\widehat{E}_1$	$\widehat{P}_1$	$\widehat{Y}_1$	$\widehat{X}_3$	$\widehat{E}_3$	$\widehat{P}_3$	$\widehat{Y}_3$	$\widehat{Y}_2$	$\widehat{P}_2$	$\widehat{Y}_{\text{tot}}$	$\widehat{U}$
47.38†	3.64	0.64	8.98†	87.42†	1.24	0.04	46.45†	11.10†	0.38	20.08†	9.8
† *in* 10^4 tons											

Steady state fish stocks are both below half the carrying capacity, reflecting the overexploited status of several reduction fisheries and of many fish stocks exploited for human consumption. At least, we focus on this scenario adopting a worst case approach. With $\widehat{X}_3$ being worth 22% of K_3, the reduction species is endangered. However, as expected, the wild edible fish stock, $\widehat{X}_1$, is higher than in the baseline situation, and as X_1^* and $\widehat{X}_1$ are both located on the left-hand side of the logistic growth function we have $\widehat{Y}_1 > Y_1^*$. Furthermore, the joint production of the two sectors, $\widehat{Y}_{\text{tot}}$, is higher than Y_1^*. Hence, $\widehat{P}_1$ drops underneath P_1^*. The existence of aquaculture lifts the threat to the survival of the wild edible species and increases consumer utility thanks to a higher production level and lower price levels i.e. $\widehat{U} > U^*$.

The price of the farmed fish is 40% lower than that of the wild edible fish. First because it is produced in larger quantity: $\widehat{Y}_1 < \widehat{Y}_2$. Secondly, because it is less valued by consumers. Here the FIFO ratio is worth $\widehat{Y}_3/\widehat{Y}_2 = 4.2$. It is slightly lower than the salmon FIFO of 4.9 reported by Tacon and Metian (2008) to account for potential improvements in FIFO ratios which have occurred since or which are to come soon. Indeed, the farmed fish remains a high value species as $\alpha_1(k)$ is calibrated such that for a 4.2 FIFO ratio the farmed product is only 10% less weighted than the wild fish.

5.1.2 The dynamics of the model with aquaculture

We simulate the transitional dynamics following the introduction of aquaculture, starting from the reference situation of an overexploited wild fishery at the steady state. Figure 1 displays paths obtained in the situation with aquaculture, given the reference calibration. Initial values of the edible fish fishery variables are set equal to their stationary values absent aquaculture: $X_{1,0} = X_1^*$, $E_{1,0} = E_1^*$. The reduction fishery is assumed to be unexploited at the initial date: $X_{3,0} = K_3$. We have shown analytically that the long run equilibrium is a stable node, implying indeterminacy regarding the initial value of the harvesting effort level. We set arbitrarily $E_{3,0} = 3$.

< Figure 1 about here >

For this initial level of effort, the introduction of aquaculture produces a dramatic drop in the feed fish stock. In less than 20 periods X_3 brushes extinction. Consequently, P_2 skyrockets with the scarcity of the farmed product. Its value exceeds that of the wild product for a few periods. Afterwards, E_3 sharply adjusts to the low level of X_3, which regains higher values. Alongside, X_1 continuously rises towards its steady state value. Even when aquaculture production is very low, the edible fish stock is better-off than in the baseline situation as aquaculture ensures a portion of the food fish supply. Specially as the wild and farmed product are strong substitute. Hence, P_1 diminishes over the time horizon. Though, before X_3 partly recovers, P_1 also soars up to the 20th period as the loss of production from aquaculture induces demand to fall back on the wild product. The hump described by E_1 around the 40th period responds to the drop in X_3 which has occurred.

The initial level of $E_{3,0}$ appears to be disproportionably high as it almost leads the reduction fishery to extinction and produces an abrupt disruption in the different trajectories. We chose this initial value of the harvesting effort to highlight the fact that even if the steady state stock level $\widehat{X}_3$ is unique and positive, and the equilibrium point is a stable node, a too high initial value of the harvesting effort may cause the collapse of the exploited resource.

5.2 Sensitivity analysis at the steady state

We now study the evolution of the steady state outcomes with respect to k, given two expressions of the preferences function $\alpha(k)$:

- $\alpha(k)$ specified in (39);
- $\alpha(k) = \alpha$, a positive constant, with $\alpha \in [\alpha_{\min}; 0.5]$.

all other parameters being set at their value of the reference calibration. In the numerical simulations exhibited in Figure 2, we set $\alpha = 0.4$. The solid curves are obtained with $\alpha(k)$, the dashed ones are obtained with α. Recall that a rising k means aquaculture produces a species less and less demanding in feed fish to thrive.

< Figure 2 about here >

The solid curves depict consumers who are obviously reluctant to eat omnivorous and by extension herbivorous species. For k low, $\widehat{X}_1$ is high at the expense of $\widehat{X}_3$. Thanks to aquaculture, the production of high quality food fish has increased, lowering fish price. Thus, fishing pressure on $\widehat{X}_1$ diminishes. However, as k becomes larger, consumers become less willing to substitute $\widehat{Y}_2$ to $\widehat{Y}_1$. Beyond a threshold value of k, the deferral of demand on $\widehat{Y}_1$ makes $\widehat{X}_1$ decline with k while $\widehat{X}_3$ recovers. Accordingly, $\widehat{P}_1$ rises at new while $\widehat{P}_2$ comes close to 0. There appears to be stock maximizing values of k, for each stock respectively. The value of k maximizing the stock $\widehat{X}_1$ also minimizes $\widehat{X}_3$, while the reverse holds. There is clearly a trade-off between both stocks.

Turning to the dashed curves, the variation in k now traduces efficiency improvement of the aquaculture technology, given a farmed species, rather than a change in the choice of the farmed species diet. Thus, it is possible to produce more of the same farmed product, alleviating pressure on $\widehat{X}_1$. But it is harmful to $\widehat{X}_3$ because the rise in k increases the productivity of a unit of $\widehat{Y}_3$, giving incitive to overexploit the feed fish stock. This observation stresses the necessity of finding a substitute for feed fish in the nourishment of farmed carnivorous species. The shortage of adapted *fish food* may narrow aquaculture's production potential or economic accessibility.

< Figure 3 about here >

Figure 3 gives consumers' utility level as a function of k. As expected, when preferences do not depend on k utility is increasing in k due to the higher global level fish food production it enables. When preferences depend on k, there exists a utility maximizing farmed species type. Consumers being sensitive to the quality of their consumption, 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.

6 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 content while population grows, and to alleviate fishing pressure on wild edible fish stocks. This article analyzes the impact of fed aquaculture on wild fish stocks and on consumer welfare, assuming preferences are carnivorous species biased. By means of the Schaefer reference model of fishery dynamics, and a simple modeling of the aquaculture technology, we give some qualitative answers to these issues. Our model encompasses three sectors: the edible fishery, the feed fishery and the aquaculture sector, and the demand side where the wild and farmed products are substitutes. 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 and stable steady state. Furthermore there exists a range of income levels for which the introduction of aquaculture prevents the wild edible species of collapsing. Indeed, by increasing global fish supply, aquaculture decreases the price of the wild product, thus, fishing effort decreases allowing the edible stock to recover. The introduction of aquaculture also benefits to consumers whose utility increases. However, the net effect of aquaculture on overall stocks is less obvious. For the global stock to be higher with aquaculture, a limited necessity and catchability of feed fish is required. In presence of aquaculture, our numerical simulations actually give a severely overexploited feed fishery and a total fish stock well below its level absent of aquaculture. This result underlines the necessity of regulating feed fisheries.

Of course, our results are conditioned by the fact that we do not account for biological interactions between both fisheries. If such interaction was added to our framework, fed aquaculture could result in a negative impact on wild edible fish stock. Adopting an ecosytemic approach counts among the improvement that could be carried to this study, but it is not the focus of our analysis. Our interest is to emphasize the influence of consumer preferences. Through comparative statistics and numerical simulations, we show that there exists a trade-off in the choice of the farmed species. The less carnivorous it is, the higher will be the pressure on the wild edible fish stock, while the more carnivorous it is, the higher will be the pressure on the feed fish stock. What also emerges from the simulations is the difficulty to satisfy a plurality of objectives. Whether it is to maximize utility, edible wild fish stock, non-edible wild fish stock or one or the other type of fish production, none of these goals are consistent.

This article raises a few research tracks that remain to be explored. As mentioned, the impact of biological interactions between species could be investigated. Such concern has been pointed in the literature in favor of an ecosystemic approach to fisheries' management. In addition, the study is carried out for fisheries in open access. The introduction of different regulatory instruments such as taxes, transferable quotas or fishing rights would change the outcomes of the model. In a policy-oriented perspective, seeking the optimal management rule of both stocks should be interesting.

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Appendix

A Uniqueness of the interior solution

Plugging the expressions of stationary stocks and efforts given by (26)–(29) into (30) yields:

$$\frac{q_1 K_1}{a(k)^{\frac{1}{\sigma-1}} k \left(\gamma q_3 K_3\right)^{\gamma}} \left(\frac{I}{c}\right)^{1-\gamma} \widehat{A}^{\frac{\sigma}{\sigma-1}} \frac{1}{1+\widehat{A}} \left(1 - \frac{q_1 I}{r_1 c} \frac{1}{1+\widehat{A}}\right) = \left(\frac{\widehat{A}}{1+\widehat{A}} \left(1 - \gamma \frac{q_3 I}{r_3 c} \frac{\widehat{A}}{1+\widehat{A}}\right)\right)^{\gamma}$$

Let $\widehat{B} = \frac{\widehat{A}}{1+\widehat{A}}$. We have $0 \leq \widehat{B} < 1$.The previous equation reads:

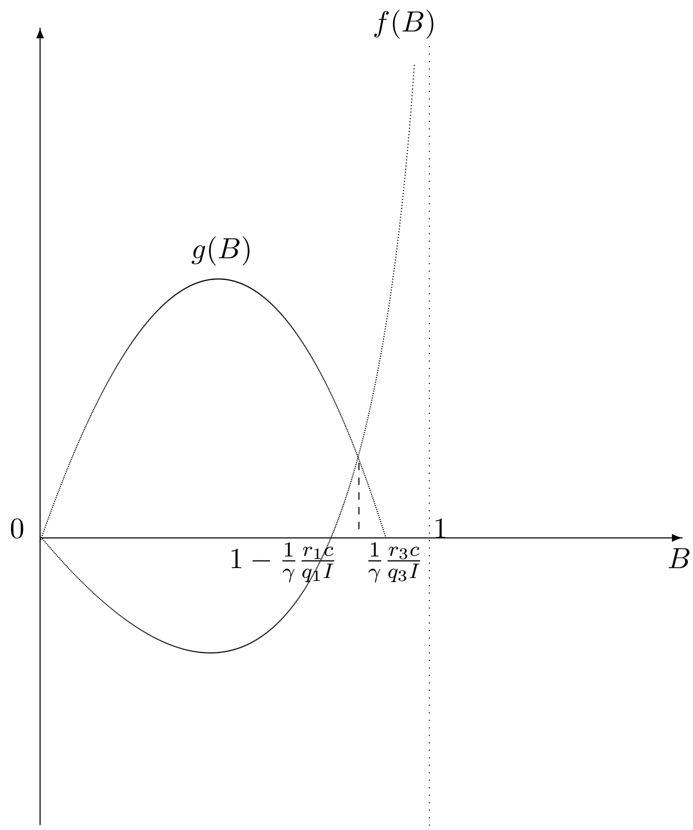
$$\frac{q_1 K_1}{a(k)^{\frac{1}{\sigma-1}} k \left(\gamma q_3 K_3\right)^{\gamma}} \left(\frac{I}{c}\right)^{1-\gamma} \left(\frac{\widehat{B}}{1-\widehat{B}}\right)^{\frac{1}{\sigma-1}} \widehat{B} \left(1 - \frac{q_1 I}{r_1 c}(1-\widehat{B})\right) = \left(\widehat{B}\left(1 - \gamma \frac{q_3 I}{r_3 c} \widehat{B}\right)\right)^{\gamma} \quad (40)$$

Figure 6 portrays the two members of this equation. The left-hand side member is denoted $f(\widehat{B})$ and the right-hand side member $g(\widehat{B})$. The condition of existence of $g(\widehat{B})$ is $1 - \gamma \frac{q_3 I}{r_3 c} \widehat{B} \geq 0$ i.e.$\widehat{B} \leq \frac{1}{\gamma} \frac{r_3 c}{q_3 I}$. $g(\widehat{B})$ is then a positive inverted U-shaped function.

- When $1 - \frac{r_1 c}{q_1 I} < 0$, $f(\widehat{B})$ is a positive function, increasing from 0 to infinity when $\widehat{B}$ increases from 0 to 1. The solution to equation $f(\widehat{B}) = g(\widehat{B})$ exists and is unique. In this case, I is sufficiently low to ensure that the wild edible fish stock is not exhausted in the long run absent aquaculture.
- The case $1 - \frac{r_1 c}{q_1 I} > 0$ and $1 - \frac{r_1 c}{q_1 I} < \frac{1}{\gamma} \frac{r_3 c}{q_3 I}$ is depicted on Figure 3. Again, the solution to equation $f(\widehat{B}) = g(\widehat{B})$ exists and is unique.
- In the case $1 - \frac{r_1 c}{q_1 I} > 0$ and $1 - \frac{r_1 c}{q_1 I} > \frac{1}{\gamma} \frac{r_3 c}{q_3 I}$, the solution does not exist.

We conclude that the condition of existence and uniqueness of an interior solution to equation (40) is

$$I < \frac{r_1 c}{q_1} + \frac{1}{\gamma} \frac{r_3 c}{q_3}$$



B Stability

The linearization of the dynamic system (25) in the neighborhood of the steady state yields the following Jacobian matrix:

$$J = \begin{pmatrix} F_1'(\widehat{X}_1) - q_1\widehat{E}_1 & -q_1\widehat{X}_1 & 0 & 0 \\ a_{21} & a_{22} - \beta c & -a_{23} & -a_{24} \\ 0 & 0 & F_3'(\widehat{X}_3) - q_3\widehat{E}_3 & -q_3\widehat{X}_3 \\ -a_{21} & -a_{22} & a_{23} & a_{24} - \beta c \end{pmatrix}$$

with

$$\begin{cases} a_{21} = \frac{\beta I}{\left(1+\widehat{A}\right)^2}\frac{\sigma-1}{\sigma}\frac{\widehat{A}}{\widehat{X}_1} \\ a_{22} = \frac{\beta I}{\left(1+\widehat{A}\right)^2}\frac{\sigma-1}{\sigma}\frac{\widehat{A}}{\widehat{E}_1} \\ a_{23} = \frac{\beta I}{\left(1+\widehat{A}\right)^2}\frac{\sigma-1}{\sigma}\gamma\frac{\widehat{A}}{\widehat{X}_3} \\ a_{24} = \frac{\beta I}{\left(1+\widehat{A}\right)^2}\frac{\sigma-1}{\sigma}\gamma\frac{\widehat{A}}{\widehat{E}_3} \end{cases}$$

Tedious computations show that the characteristic polynomial reads:

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

with

$$\begin{aligned} Q(\lambda) = {} & \lambda^3 + \left[\frac{\beta c}{\sigma} - H_1 - H_3\right]\lambda^2 \\ & + \left[\frac{\beta c}{\sigma}(-H_1 - H_3) + H_1 H_3 + \frac{\sigma - 1}{\sigma}\frac{\beta I \widehat{A}}{\left(1+\widehat{A}\right)^2}(q_1 + \gamma q_3)\right]\lambda \\ & + \frac{\beta c}{\sigma} H_1 H_3 - \frac{\sigma - 1}{\sigma}\frac{\beta I \widehat{A}}{\left(1+\widehat{A}\right)^2}(q_1 H_3 + \gamma q_3 H_1) \end{aligned}$$

and

$$\begin{cases} H_1 = F_1'(\widehat{X}_1) - \frac{F_1(\widehat{X}_1)}{\widehat{X}_1} < 0 \\ H_3 = F_3'(\widehat{X}_3) - \frac{F_3(\widehat{X}_3)}{\widehat{X}_3} < 0 \end{cases}$$

$P(\lambda)$ admits one negative real root equal to $-\beta c$, plus the 3 roots of $Q(\lambda)$. We apply the Routh-Hurwitz criterion to $Q(\lambda)$:

$$Q(\lambda) = b_3\lambda^3 + b_2\lambda^2 + b_1\lambda + b_0$$

with

$$\begin{cases} b_3 = 1 > 0 \\ b_2 = \frac{\beta c}{\sigma} - H_1 - H_3 > 0 \\ b_1 = \frac{\beta c}{\sigma}(-H_1 - H_3) + H_1 H_3 + \frac{\sigma-1}{\sigma}\frac{\beta I \widehat{A}}{\left(1+\widehat{A}\right)^2}(q_1 + \gamma q_3) > 0 \\ b_0 = \frac{\beta c}{\sigma} H_1 H_3 - \frac{\sigma-1}{\sigma}\frac{\beta I \widehat{A}}{\left(1+\widehat{A}\right)^2}(q_1 H_3 + \gamma q_3 H_1) > 0 \\ b_2 b_1 - b_3 b_0 = \left[\left(\frac{\beta c}{\sigma}\right)^2 + H_1 H_3\right](-H_1 - H_3) + \frac{\sigma-1}{\sigma}\frac{\beta I \widehat{A}}{\left(1+\widehat{A}\right)^2}\left[\frac{\beta c}{\sigma}(q_1 + \gamma q_3) - q_1 H_1 - \gamma q_3 H_3\right] + \frac{\beta c}{\sigma}(H_1 + H_3)^2 > 0 \end{cases}$$

We conclude that the linearized dynamic system is stable (see Gantmacher, 1959).

C Comparative statics

From system (26)–(30) we get:

$$d\widehat{X}_1 = K_1 \frac{q_1 I}{r_1 c} \frac{d\widehat{A}}{\left(1+\widehat{A}\right)^2}$$

$$d\widehat{E}_1 = -\frac{I}{c} \frac{d\widehat{A}}{\left(1+\widehat{A}\right)^2}$$

$$d\widehat{X}_3 = -K_3 \gamma \frac{q_3 I}{r_3 c} \frac{d\widehat{A}}{\left(1+\widehat{A}\right)^2}$$

$$d\widehat{E}_3 = \gamma \frac{I}{c} \frac{d\widehat{A}}{\left(1+\widehat{A}\right)^2}$$

and

$$\begin{aligned}
\frac{d\widehat{A}}{\widehat{A}} &= \frac{1}{\sigma}\frac{ka'(k)}{a(k)}\frac{dk}{k} + \frac{\sigma-1}{\sigma}\left(\frac{dk}{k} + \gamma\frac{d\widehat{E}_3}{\widehat{E}_3} + \gamma\frac{d\widehat{X}_3}{\widehat{X}_3} - \frac{d\widehat{E}_1}{\widehat{E}_1} - \frac{d\widehat{X}_1}{\widehat{X}_1}\right) \\
&= \frac{1}{\sigma}\frac{ka'(k)}{a(k)}\frac{dk}{k} + \frac{\sigma-1}{\sigma}\frac{dk}{k} + \frac{\sigma-1}{\sigma}\left(\gamma\frac{1}{1+\widehat{A}} - \gamma\frac{\gamma\frac{q_3 I}{r_3 c}\frac{\widehat{A}}{1+\widehat{A}}}{1-\gamma\frac{q_3 I}{r_3 c}\frac{\widehat{A}}{1+\widehat{A}}}\frac{1}{1+\widehat{A}} + \frac{\widehat{A}}{1+\widehat{A}} - \frac{\frac{q_1 I}{r_1 c}\frac{1}{1+\widehat{A}}}{1-\frac{q_1 I}{r_1 c}\frac{1}{1+\widehat{A}}}\frac{\widehat{A}}{1+\widehat{A}}\right)\frac{d\widehat{A}}{\widehat{A}} \\
&= \frac{1}{\sigma}\left(\frac{ka'(k)}{a(k)} + (\sigma-1)\right)\frac{dk}{k} + \frac{\sigma-1}{\sigma}\frac{1}{1+\widehat{A}}\left(\gamma - \gamma\frac{1-\frac{\widehat{X}_3}{K_3}}{\frac{\widehat{X}_3}{K_3}} + \widehat{A} - \frac{1-\frac{\widehat{X}_1}{K_1}}{\frac{\widehat{X}_1}{K_1}}\widehat{A}\right)\frac{d\widehat{A}}{\widehat{A}}
\end{aligned}$$

hence:

$$\left[1 - \frac{\sigma-1}{\sigma}\frac{1}{1+\widehat{A}}\left(\gamma\left(2-\frac{K_3}{\widehat{X}_3}\right) + \widehat{A}\left(2-\frac{K_1}{\widehat{X}_1}\right)\right)\right]\frac{d\widehat{A}}{\widehat{A}} = \frac{1}{\sigma}\left(\frac{ka'(k)}{a(k)} + (\sigma-1)\right)\frac{dk}{k}$$

As for catches, we obtain:

$$\frac{d\widehat{Y}_1}{\widehat{Y}_1} = \frac{d\widehat{E}_1}{\widehat{E}_1} + \frac{d\widehat{X}_1}{\widehat{X}_1} = \left(\frac{\frac{q_1 I}{r_1 c}\frac{1}{1+\widehat{A}}}{1-\frac{q_1 I}{r_1 c}\frac{1}{1+\widehat{A}}} - 1\right)\frac{d\widehat{A}}{1+\widehat{A}} = \left(\frac{K_1}{\widehat{X}_1} - 2\right)\frac{d\widehat{A}}{1+\widehat{A}}$$

$$\frac{d\widehat{Y}_2}{\widehat{Y}_2} = \frac{dk}{k} + \gamma\left(\frac{d\widehat{E}_3}{\widehat{E}_3} + \frac{d\widehat{X}_3}{\widehat{X}_3}\right) = \frac{dk}{k} + \gamma\left(2 - \frac{K_3}{\widehat{X}_3}\right)\frac{1}{\widehat{A}}\frac{d\widehat{A}}{1+\widehat{A}}$$

Finally, for prices, we have:

$$\frac{d\widehat{P}_1}{\widehat{P}_1} = -\frac{d\widehat{A}}{1+\widehat{A}} - \frac{d\widehat{Y}_1}{\widehat{Y}_1} = -\left(\frac{K_1}{\widehat{X}_1} - 1\right)\frac{d\widehat{A}}{1+\widehat{A}}$$
$$\frac{d\widehat{P}_2}{\widehat{P}_2} = \frac{d\widehat{A}}{\widehat{A}} - \frac{d\widehat{A}}{1+\widehat{A}} - \frac{d\widehat{Y}_2}{\widehat{Y}_2} = -\frac{dk}{k} + \left[1 - \gamma\left(2 - \frac{K_3}{\widehat{X}_3}\right)\right]\frac{1}{\widehat{A}}\frac{d\widehat{A}}{1+\widehat{A}}$$

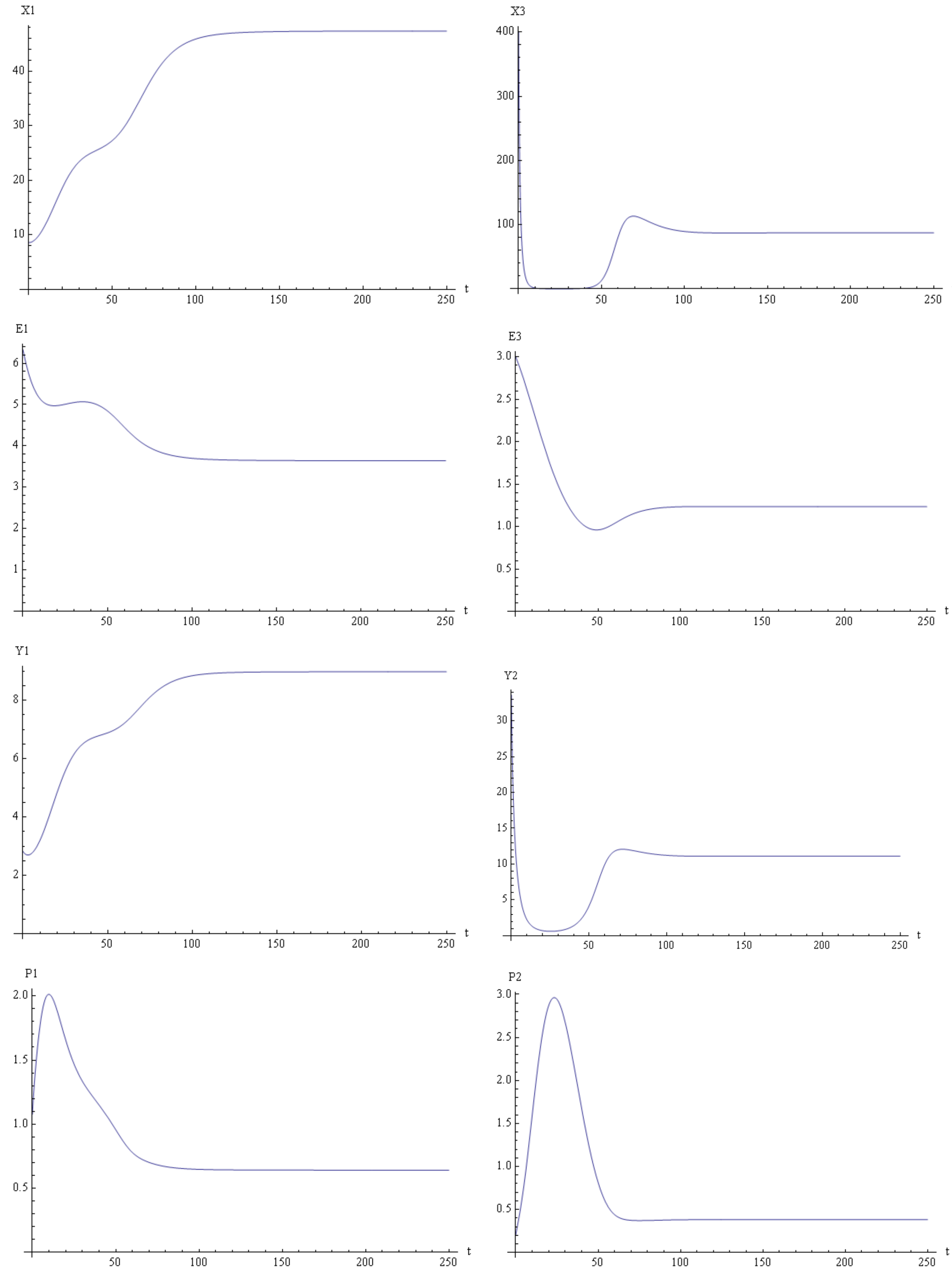


Figure 1: Dynamic effects of the introduction of aquaculture

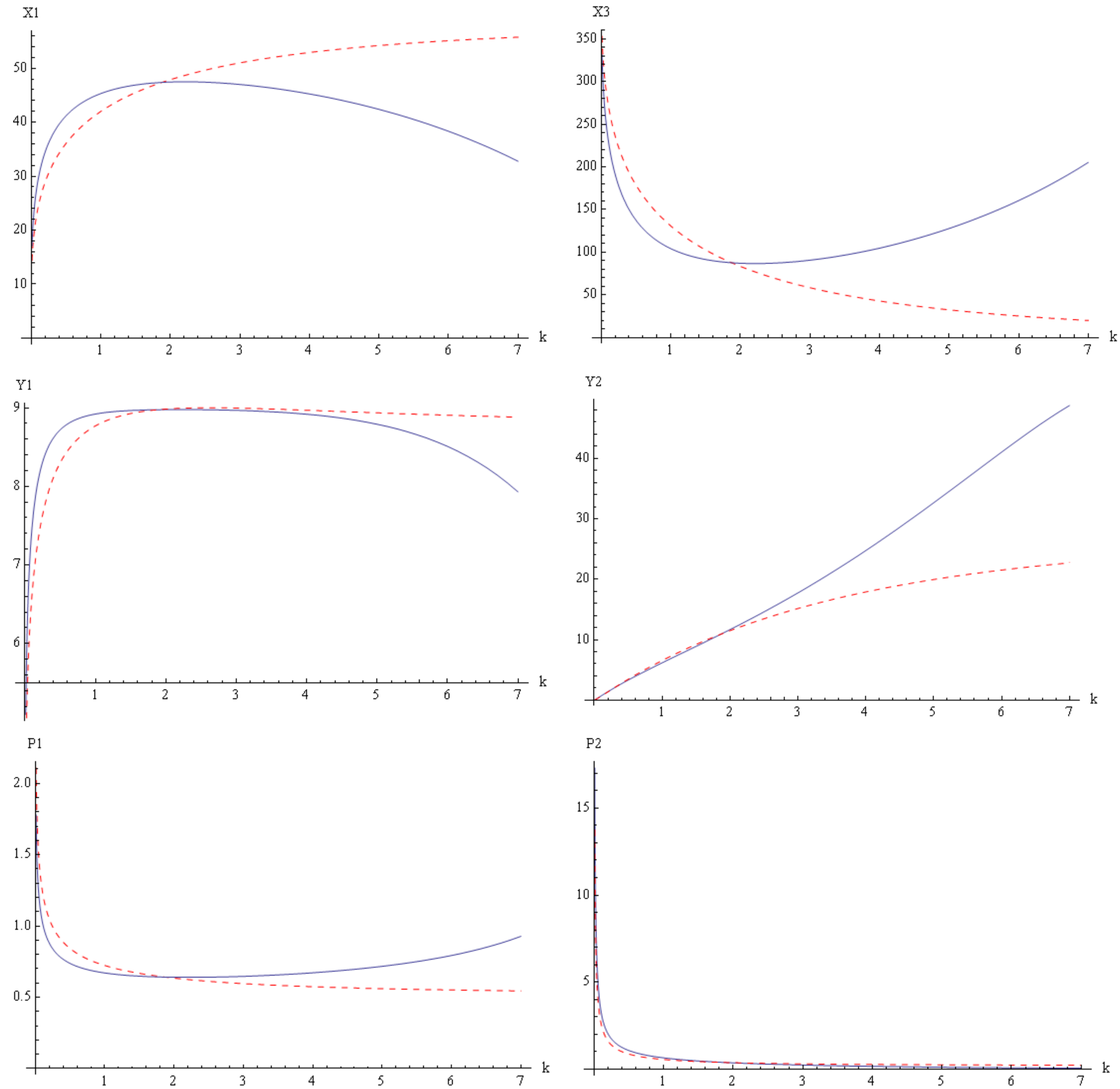


Figure 2: Influence of k on steady state outcomes for two specifications of $\alpha(k)$

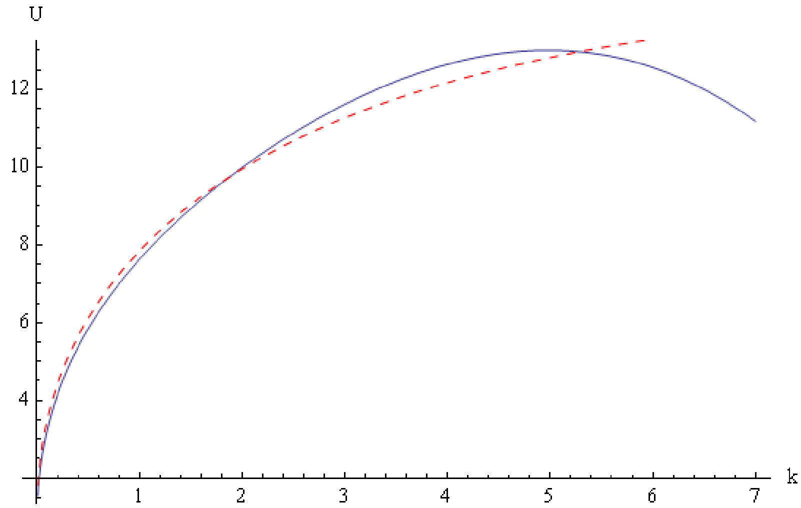


Figure 3: Influence of k on consumers' utility for two specifications of $\alpha(k)$