The Influence of Consumer Preferences on Aquaculture Technology and the Sustainability of Fisheries

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Introduction

- 50% of world marine fish stocks are fully exploited, 32% are overexploited (FAO 2010).
- The maximum capture fishery potential from world's oceans has been reached.
- Aquaculture: is it really an option?
  - Annual average growth rate of aquaculture from 1970 to 2008: 8.3% (FAO 2010).
  - In 2010, capture fisheries managed to provide 9 kg of food fish per capita, per year, versus 8.6 kg for aquaculture (FAO 2010).
  - But the production methods of aquaculture present limitations in terms of environmental sustainability.

- Aquaculture depends on natural populations for the feeding of 48% of its production (FAO & IFFO data).
- In 2009 it consumed 63% of fishmeal and 81% of fish oil world production (IFFO).
- FIFO: number of tons of wild fish necessary to produce 1 ton of farmed fish.
- Tacon and Metian (2008), Naylor *et al.* (2009): for carnivorous species (salmon) FIFO reaches 4.9.
- The more carnivorous the farmed fish species is, the better for consumers (at least in western countries) but the more inefficient the production technique.

Literature review

- Market interactions:
  Anderson (1985, *MRE*); Ye and Beddington (1996, *MRE*)
- Biological interactions:
  Hanesson (2003, *Marine Policy*)

Motivation

▶*Investigate the impact of aquaculture production on wild fish stocks, taking into account two key components: (1) its dependence on reduction fisheries; (2) consumers preferences.*
▶*We answer this question focusing on the food fish demand arising from wealthy countries.*

- Stylized model including the demand side and three productive sectors: a edible fish fishery, a reduction fishery and the aquaculture sector.
- Wild and farmed fish are strong (but not perfect) substitutes.
- Study the long term outcomes and the short term adjustments of fish stocks, supply and prices.

The demand side

- Utility function of the representative consumer:

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

  Y_1: wild species
  Y_2: farmed fish
  σ: elasticity of substitution between wild and farmed fish

- $k \in]0, k_{\max}]$: efficiency of aquaculture in converting feed fish into farmed fish
  - the lower k the less efficient aquaculture is, and the higher the FIFO ratio
  - the lower k the more carnivorous the farmed fish is, and the more consumers like it.
- $\alpha(k) \in [\alpha_{min}; 0.5[$: weights consumers' preferences for each type of fish; $\alpha'(k) < 0$

- Consumer's budget constraint:

$$P_{1t}Y_{1t} + P_{2t}Y_{2t} = I$$

$\rightarrow$*Partial equilibrium: consumers' spending on fish exogenous*

- Demand functions for the two types of fish:

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

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

with

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

The supply side
The fisheries

- Dynamics of the edible fish (species 1) and feed fish (species 3) fisheries described by the Schaefer model (1954):

$$\begin{cases} \dot{X}_{it} = F_i(X_{it}) - Y_{it} \\ \dot{E}_{it} = \beta\pi_{it} = \beta(P_{it}Y_{it} - cE_{it}), \quad \beta > 0 \end{cases}$$

with

$$F_i(X_{it}) = r_i X_{it}\left(1 - \frac{X_{it}}{K_i}\right)$$
$$Y_{it} = q_i E_{it} X_{it}$$

where $i = 1, 3$, X_i:stock level; E_i: effort level; K_i: carrying capacity; q_i: catchability coefficient; r_i: intrinsic growth rate of the population;

The supply side

The aquaculture sector

- In the aquaculture sector farmers are in competition on the farmed fish (species 2) market.

- At each date farmers demand the input quantity of feed fish such as to maximize their profit:

$$\pi_{2t} = P_{2t}Y_{2t} - P_{3t}Y_{3t}$$

- Production function:

$$Y_{2t} = k(Y_{3t})^{\gamma}, \quad \gamma \in]0,1[$$

k: efficiency of the aquaculture sector

- From the production function, we have:

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

The baseline situation: capture fishery alone

- The demand function reduces to:

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

$\rightarrow$ *The price elasticity of demand is unitary.*

- We add to the previous dynamic system the equilibrium of the wild fish market at each date $Y_{1t} = Y_1^d(P_{1t})$.

- Eliminating P_1 and Y_1 yields:

$$\begin{cases} \dot{X}_{1t} = F_1(X_{1t}) - q_1 E_{1t} X_{1t} \\ \dot{E}_{1t} = \beta\,(I - cE_{1t}) \end{cases}$$

- The unique stationary stock and effort are:

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

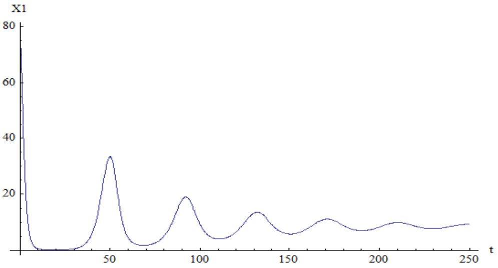
$$E_1^* = \begin{cases} \frac{I}{c} \text{ iff } \frac{q_1 I}{r_1 c} < 1 \\ 0 \text{ otherwise} \end{cases}$$

$\rightarrow$ *if* $\frac{q_1 I}{r_1 c} \geq 1$ *wild fish is doomed to extinction in the long run.*

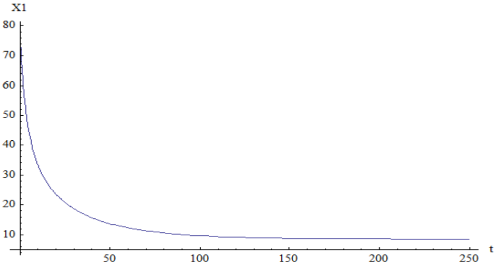
- The steady state is a stable node.

- The permanent fitting of price to equalize supply and demand results in smooth trajectories compared to the Textbooks' case of infinite elasticity of demand (Clark, 1990 for instance).

Dynamics of the capture fishery alone



P1 constant



P1 endogenous

The coupling

- We equalize supplies and demands to reach equilibrium on all 3 fish markets:
- The final dynamic system is:

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

with

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

- The nature of the steady state, derived from this 4 dimensions matrix, is a stable node.

Steady state outcomes

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

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

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

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

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

Capture fishery alone:

$$X_1^* = K_1\left(1 - \frac{q_1 I}{r_1 c}\right)$$

$$E_1^* = \frac{I}{c}$$

Proposition 1

- $\widehat{X}_1 > X_1^*$ and $\widehat{E}_1 < E_1^*$: Aquaculture alleviates pressure on the wild edible fish stock in the long run.
- Moreover, as $\widehat{P}_1^* = \frac{c}{q_1 \widehat{X}_1^*}$, the wild edible fish price is always lower in the long run in presence of aquaculture. Thus, we have

$$\frac{\partial \widehat{X}_1}{\partial \widehat{Y}_2} > 0 \Leftrightarrow \frac{\partial \widehat{P}_1}{\partial \widehat{Y}_2} < 0$$

- Finally, $Y_1^* < \widehat{Y}_1$.
  - always satisfied when $X_1^* < \widehat{X}_1 < K_1/2$,
  - never satisfied in the opposite case: $K_1/2 < X_1^* < \widehat{X}_1$.
  - may also be satisfied when the stock is overexploited in the reference situation and becomes larger that $K_1/2$ in the presence of aquaculture.
- In any event, it seems obvious that $Y_1^* < \widehat{Y_1} + \widehat{Y_2}$, else aquaculture would have no reasons to be.

Proposition 2

- Condition of coexistence of aquaculture and the edible fish fishery:

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

  - $\frac{r_1 c}{q_1}$ is the maximum admissible incomes for the existence in the long run of the capture fishery alone
  - $\frac{1}{\gamma}\frac{r_3 c}{q_3}$ idem for aquaculture alone.

$\rightarrow$*in presence of aquaculture, the capture fishery can bear a higher income level.*

- Under this condition, the interior steady state is unique.

Proposition 3

- Eliminating $\widehat{A}$ yields:

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

- Total effective long run level of harvesting effort: $\widehat{E}_1 + \widehat{E}_3$.
- Virtual total level of effort: I/c, constant (Remember that absent aquaculture the optimal level of effort in the capture fishery is $E_1^* = I/c$).
- It must be splitted into:
  - an effective effort $\widehat{E}_1$ devoted to catch the edible wild species,
  - 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.

The choice of the farmed species

Influence of the choice of the farmed species, k, on the steady state variables

$$\frac{d\widehat{X}_1}{d\widehat{A}} > 0, \quad \frac{d\widehat{E}_1}{d\widehat{A}} < 0, \quad \frac{d\widehat{X}_3}{d\widehat{A}} < 0, \quad \frac{d\widehat{E}_3}{d\widehat{A}} > 0$$

and

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

- If $\widehat{X}_1 < \frac{K_1}{2}$ and $\widehat{X}_3 < \frac{K_3}{2}$, the left-hand side member of this equation is unambiguously positive.
- If $a'(k) = 0$: the right-hand side member is also positive $\Leftrightarrow$ $\frac{d\widehat{A}}{dk} > 0$.
- If $a'(k) \neq 0$ the process can be reverses: there exists a threshold value of the parameter k above which $\frac{d\widehat{A}}{dk} < 0$ and under which $\frac{d\widehat{A}}{dk} > 0$ (depending on $\alpha(k)$).

Numerical Simulations

Simulation of the evolution of the steady state outcomes according to the parameters k

- We test the following specifications of the preference function:

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

$$\alpha(k) = C;$$

with $\alpha_{\min}$ the minimum and $\alpha_{\max}$ the maximum weight affected to Y_2.

Table: Calibration of the model.

K_1	r_1	q_1	I	c	β	σ	K_3	r_3	q_3	γ	k	$\alpha_{\min}$	$\alpha_{\max}$	$k_{\max}$	C
100	0.36	0.052	10	1.58	0.05	2	400	0.68	0.43	0.46	1.9	0.1	0.55	7.5	0.4

K_1, K_3: 10^4 *tons*; r_1, r_3: *years*$^{-1}$; k: *kg*; c, I: \$

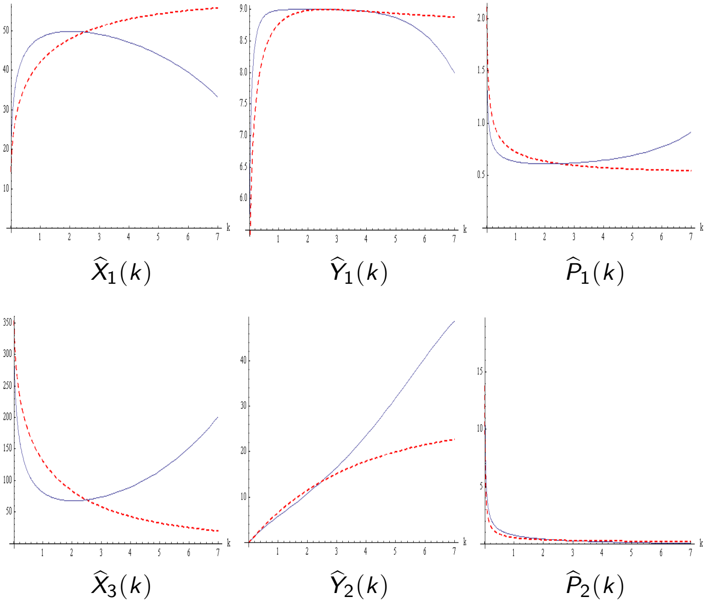


Figure: Steady state outcomes as a function of k for two specification of $\alpha(k)$

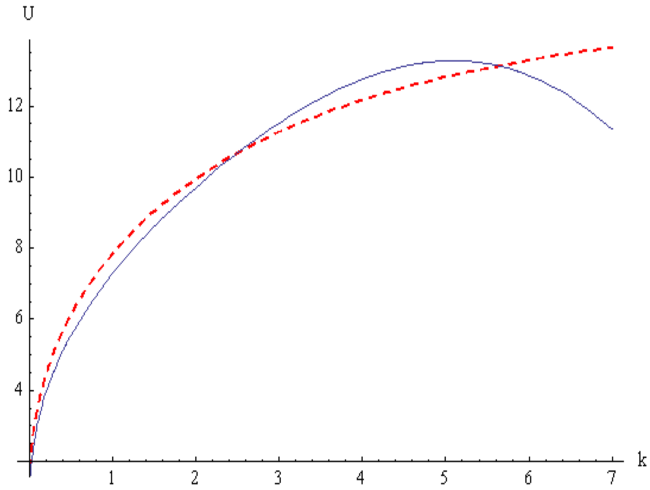


Figure: Consumers' utility as a function of k, for two specification of $\alpha(k)$.

Conclusion

▶Many hopes are placed in aquaculture.

For substitutable wild and farmed products:

- Aquaculture provides social benefits by decreasing food fish prices and increasing global supply.
- Aquaculture reduces harvesting pressure on wild edible fish stocks.

- The fact that fed aquaculture relies on a limited input narrows its stainability, production potential and economic accessibility.
- The different causes that can be pursued are hardly compatible: $maxU$, $max\pi$, $maxX_1$, $maxX_3$, $maxY_{tot}$ ...

- What are the potential options in order to improve aquaculture's sustainability?
  - Improving FIFO ratios trough technological progress, by genetically modifying farmed species, finding a relevant substitute to feed fish;
  - Modifying consumer preferences?
  - Offering the appropriate farmed substitute product?

▶What remains to be done?

- Account for biological interaction between edible and feed fish (ecosystemic approach).
- Seek for the optimal management strategy
- Further investigations are needed to shade light on consumers' behavior towards farmed products:
  What is the true shape of α?
  It may depend on species considered, countries' consumption habits, etc.