Is Aquaculture Really an Option?

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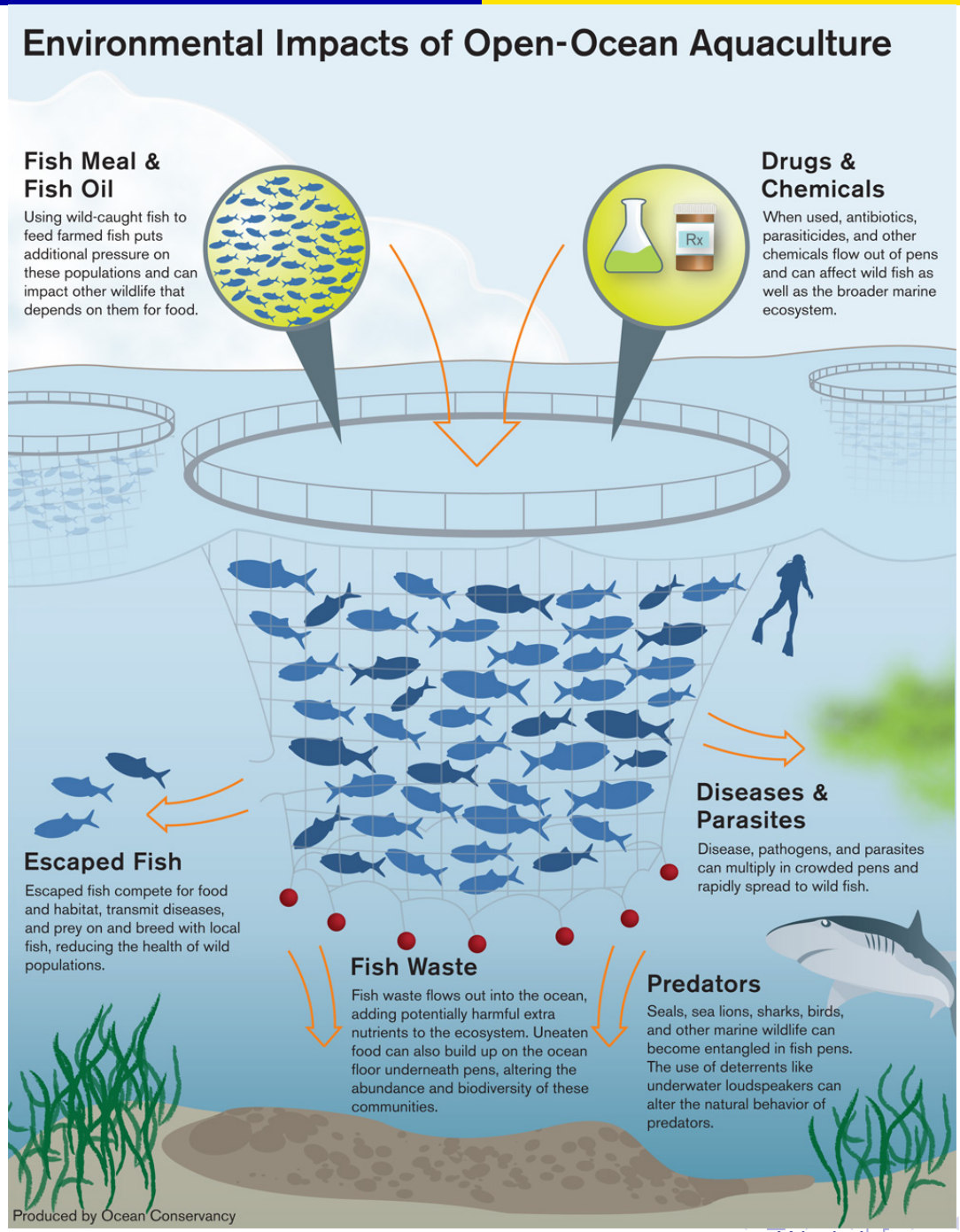
Introduction

- Breeding of terrestrial animals substituted to hunting about 8 000 years ago, but aquaculture has not replaced fishing until now. Why?
- Population growth and increase in standards of living in developing countries $\Longrightarrow$ growing demand for animal protein.
- However,
  - increase of breeding limited by land use conflicts, and
  - the maximum capture fishery potential from world's oceans has been reached (50% of world marine fish stocks are fully exploited, 32% are overexploited (FAO 2010)).

Is aquaculture really an option?

- Annual average growth rate of aquaculture from 1970 to 2008: 8.3% (FAO 2010). Fastest growing food industry.
- Aquaculture represented 27 % of world fish production in 2000, 38 % in 2009.
- But the technology presents limitations in terms of environmental sustainability:
  - inland and coastal farms cause the destruction of natural habitats;
  - release of untreated water and feeces damages ecosystems (pathogen invasion);
  - use of fertilizers $\Longrightarrow$ euthrophication;
  - aquaculture depends on low value wild fish as an input.
- FIFO: number of tons of wild fish necessary to produce 1 ton of farmed fish. For carnivorous species (salmon) it may reach $\simeq 5$.


Environmental Impacts of Open-Ocean Aquaculture
Fish Meal & Fish Oil
Using wild-caught fish to feed farmed fish puts additional pressure on these populations and can impact other wildlife that depends on them for food.
Drugs & Chemicals
When used, antibiotics, parasiticides, and other chemicals flow out of pens and can affect wild fish as well as the broader marine ecosystem.
Rx
Diseases & Parasites
Disease, pathogens, and parasites can multiply in crowded pens and rapidly spread to wild fish.
Escaped Fish
Escaped fish compete for food and habitat, transmit diseases, and prey on and breed with local fish, reducing the health of wild populations.
Fish Waste
Fish waste flows out into the ocean, adding potentially harmful extra nutrients to the ecosystem. Uneaten food can also build up on the ocean floor underneath pens, altering the abundance and biodiversity of these communities.
Predators
Seals, sea lions, sharks, birds, and other marine wildlife can become entangled in fish pens. The use of deterrents like underwater loudspeakers can alter the natural behavior of predators.
Produced by Ocean Conservancy

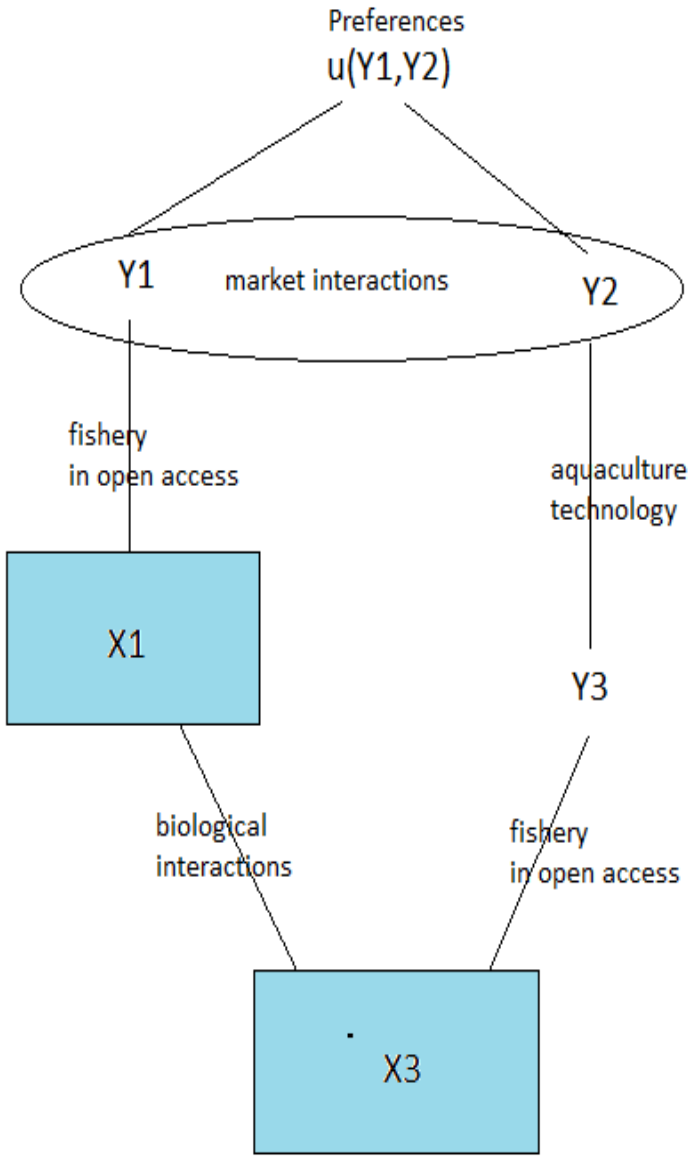
Literature review

- Very few papers.
- Market interactions, when wild and farmed fish are perfect or imperfect substitutes: Anderson (MRE 1985); Ye and Beddington (MRE 1996).
  Baseline situation: wild fishery in open access. Introduction of aquaculture: beneficial (in the long run, increases total fish supply, reduces consumer price, increases wild fish stock).
- Biological interactions: the wild edible fish feeds on the same low value fish that aquaculture uses as an input: Hanesson (Marine Policy, 2003).
  Edible wild fish and farmed fish are supposed to be the same.
  Numerical simulations show that the introduction of aquaculture is beneficial.

Motivation

Investigate the impact of aquaculture on fish consumption, welfare and wild fish stocks, taking into account:

1. its dependence on reduction fisheries;
2. consumer preferences;
3. biological interactions.



Stylized model including the demand side, an edible fish fishery, a reduction fishery and aquaculture, where:

- fisheries are in open access;
- wild edible fish and farmed fish are strong substitutes;
- aquaculture harvests feed fish to grow farmed fish; the wild edible fish feeds on the same stock.
- the more carnivorous the farmed fish species is, the more inefficient its production technology but the more consumers like it.

The demand side

Utility function of the representative consumer:

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

Y_1 / Y_2: consumption of wild edible fish / farmed fish
$\sigma > 1$: elasticity of substitution
$k \in]0, k_{\max}]$: efficiency of aquaculture in converting feed fish into farmed fish
The lower k

- the less efficient aquaculture is (the higher the FIFO)
- 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;
$\alpha'(k) < 0$
Partial equilibrium: consumers' total spending on fish I exogenous and stationary

Biological interactions

- Biological interactions between the two wild species may exist or not (Peruvian anchovy and Norwegian farmed salmon).
- When they exist, they are of the predator-prey type. Species 1 (high-value edible species) is the predator, species 3 (a low-value pelagic species) the prey.
- Evolution of the 2 stocks:

$$\dot{X}_{1t} = F_1(X_{1t}, X_{3t})$$
$$\dot{X}_{3t} = F_3(X_{1t}, X_{3t})$$

with

$$F_1(X_{1t}, X_{3t}) = a_1 X_{1t} - b_1 X_{1t}^2 + d_1 X_{1t} X_{3t}$$
$$F_3(X_{1t}, X_{3t}) = a_3 X_{3t} - b_3 X_{3t}^2 + d_3 X_{1t} X_{3t}$$

$d_1 \geq 0$, $d_3 \leq 0$; b_1, $b_3 \geq 0$; $a_1 \geq 0$, $a_3 > 0$.

4 possible long run steady states absent human intervention:

1. collapse of both populations;
2. collapse of population 1 only;
3. collapse of population 3 only;
4. coexistence of both populations:

$$\widetilde{X}_1 = \frac{b_3}{b_1 b_3 - d_1 d_3}\left(a_1 + \frac{a_3 d_1}{b_3}\right)$$
$$\widetilde{X}_3 = \frac{d_3}{b_1 b_3 - d_1 d_3}\left(a_1 + \frac{a_3 b_1}{d_3}\right)$$

Condition of existence of this SS:

$$\frac{a_1}{b_1} < -\frac{a_3}{d_3}$$

Under this condition the unique stable SS is SS 4; otherwise, it is SS 3 $\Longrightarrow$ this condition is supposed to be satisfied.

The baseline situation: capture fishery alone

- Harvest:

$$Y_{1t} = q_1 E_{1t} X_{1t}$$

  q_1: catchability coefficient; E_{1t} : effort.

- Effort E_1 adjusts to resource rent:

$$\dot{E}_{1t} = \beta \left(P_{1t} Y_{1t} - c E_{1t} \right)$$

- Demand function:

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

- Equilibrium of the wild fish market at each date: $Y_{1t} = Y_1^d(P_{1t})$.
- Eliminating P_1 and Y_1 yields:

$$\begin{cases} \dot{X}_{1t} = F_1(X_{1t}, X_{3t}) - q_1 E_{1t} X_{1t} \\ \dot{E}_{1t} = \beta \left(I - c E_{1t} \right) \\ \dot{X}_{3t} = F_3(X_{1t}, X_{3t}) \end{cases}$$

Again, 4 possible steady states:

1. collapse of both populations;
2. collapse of population 1 only;
3. collapse of population 3 only;
4. coexistence of both populations:

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

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

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

- SS 3 irrelevant by assumption (both species coexist absent human intervention; fishing the predator cannot worsen things for the prey).
- Condition of existence of SS 4:

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

- I_w : maximum revenue consumers can spend on fish without inducing the extinction of the edible species. Increasing function of d_1.
- When $I < I_w(d_1)$, the relevant SS is the interior SS 4; it is globally stable (stable node or a stable focus, depending on the parameters).
- Otherwise, species 1 collapses in the long run and the relevant SS is SS 2.

The aquaculture sector and feed fishery

- Feed fishery (species 3):

$$\begin{aligned} \dot{X}_{3t} &= F_3(X_{1t}, X_{3t}) - Y_{3t} \\ \dot{E}_{3t} &= \beta\left[P_{3t} Y_{3t} - cE_{3t}\right] \\ Y_{3t} &= q_3 E_{3t} X_{3t} \end{aligned}$$

- Aquaculture: farmers are in competition on the farmed fish (species 2) market.
- Production function:

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

k: efficiency of the aquaculture sector

The coupling

- Prices adjust so that the 3 fish markets are in equilibrium.
- Final dynamic system:

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

where $A_t \in]0, 1[$ characterizes market interactions.

Interior steady state

Capture fishery + aquaculture

$$\widehat{X}_1 = \frac{b_3}{\Lambda}\left(x_1 + y_1\widehat{A}\right)$$
$$\widehat{E}_1 = \frac{I}{c}(1-\widehat{A})$$
$$\widehat{X}_3 = \frac{d_3}{\Lambda}\left(x_3 + y_3\widehat{A}\right)$$
$$\widehat{E}_3 = \gamma\frac{I}{c}\widehat{A}$$
$$\widehat{A} = \frac{\alpha(k)}{1-\alpha(k)}\left(\frac{k\left(q_3\widehat{E}_3\widehat{X}_3\right)^{\gamma}}{q_1\widehat{E}_1\widehat{X}_1}\right)^{\frac{\sigma-1}{\sigma}}$$

Capture fishery alone

$$X_1^* = \frac{b_3}{\Lambda}x_1$$
$$E_1^* = \frac{I}{c}$$
$$X_3^* = \frac{d_3}{\Lambda}x_3$$

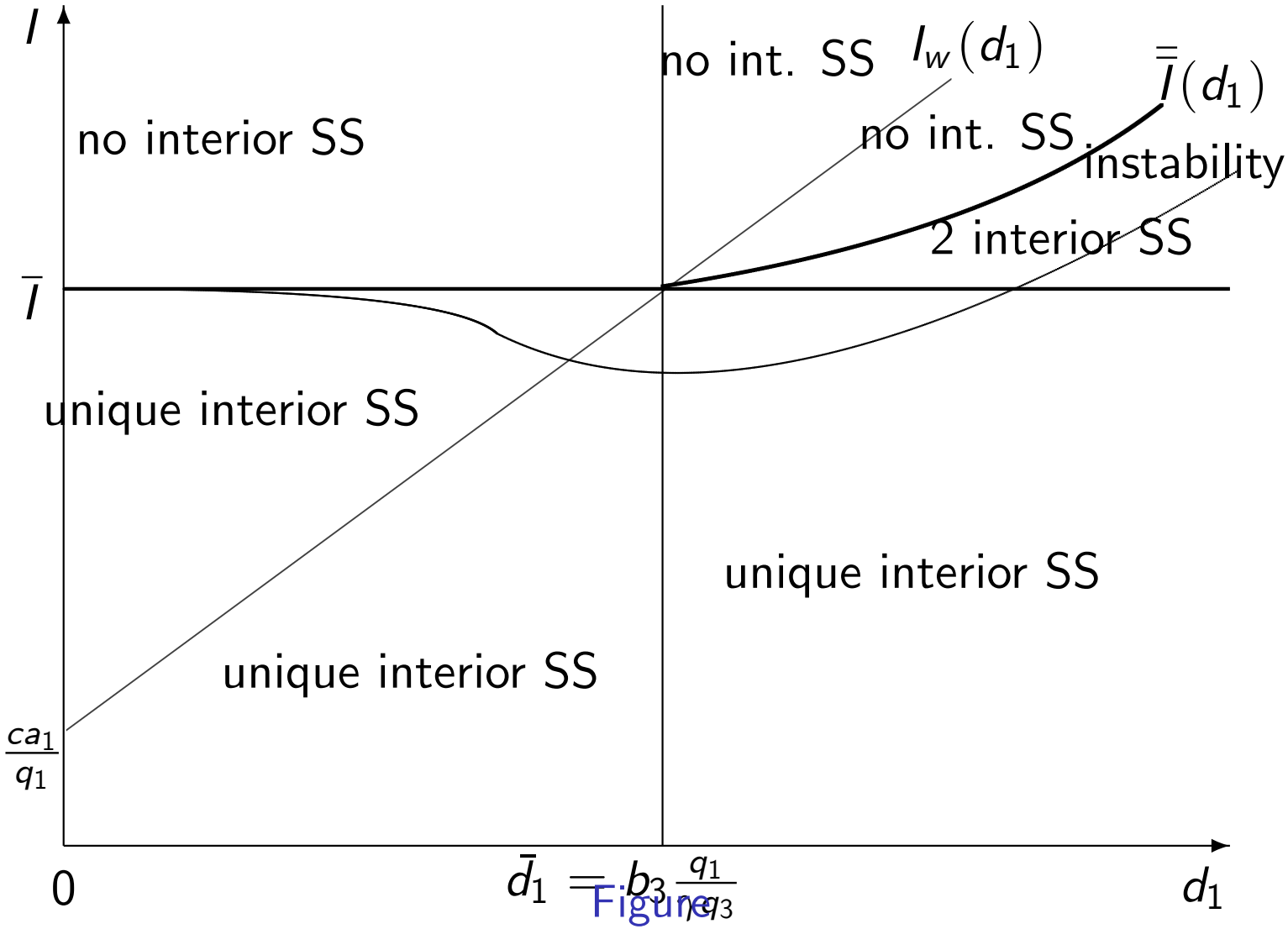
$$\Lambda = b_1 b_3 - d_1 d_3,$$
$$x_1 = a_1 + \frac{a_3 d_1}{b_3} - \frac{q_1 I}{c},\ y_1 = \left(q_1 - \frac{d_1}{b_3}\gamma q_3\right)\frac{I}{c},$$
$$x_3 = a_1 + \frac{a_3 b_1}{d_3} - \frac{q_1 I}{c},\ y_3 = \left(q_1 - \frac{b_1}{d_3}\gamma q_3\right)\frac{I}{c}$$

Proposition

(i) A sufficient condition of existence of an interior SS is:

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

Under this condition, the interior SS is unique.
(ii) Absent biological interactions ($d_1 = d_3 = 0$), the unique interior SS, when it exists, is globally stable; this remains true when biological interactions are moderate (sufficient conditions for stability are: $d_1 \leq b_3 \frac{q_1}{q_3}$, $-d_3 \leq \frac{b_1}{\gamma}$). Whatever the level of biological interactions, if the revenue spent on fish I is sufficiently small, the unique SS is globally stable.
(iii) If $I \geq \bar{I}$, when $d_1 \leq \overline{d}_1 = b_3 \frac{q_1}{\gamma q_3}$, there is no interior SS; but when $d_1 > \overline{d}_1$ there may exist 2, 1 or no interior SS.


I
$\bar{I}$
$\frac{ca_1}{q_1}$
0
$\bar{d}_1 = b_3\frac{q_1}{q_3}$
d_1
$I_w(d_1)$
$\bar{\bar{I}}(d_1)$
no int. SS
no int. SS
instability
2 interior SS
no interior SS
unique interior SS
unique interior SS
unique interior SS

Figure

- To go further on stability, numerical simulations (assumption: d_3 / d_1 remains the one of the reference calibration when d_1 varies). Show that:
  - in the region where there exist 2 SS, either both are unstable or one is unstable and the other stable, the stable one corresponding to the smaller $\widehat{A}$.
  - the interior SS may become unstable before or after $\bar{I}$ is reached; then simultaneous collapse of the 2 wild fish stocks.

Comparison with the baseline

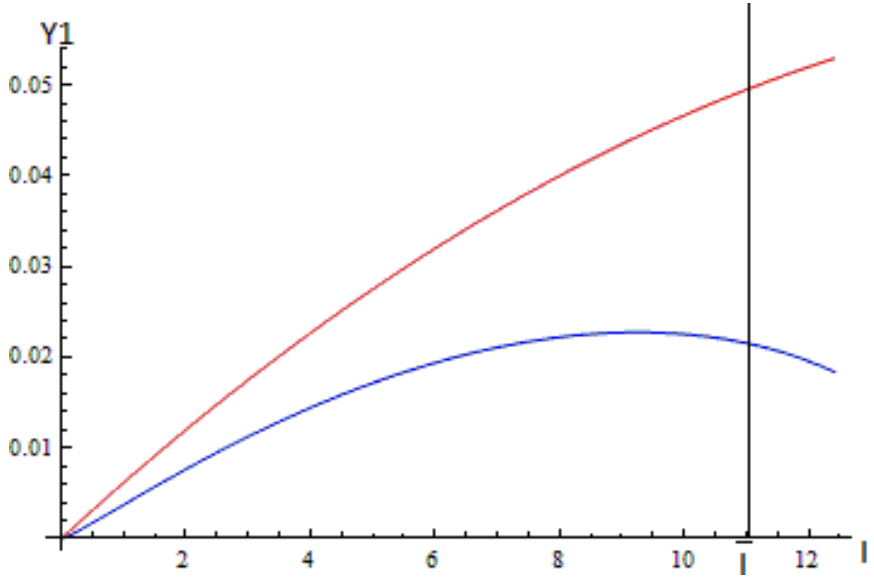
Proposition

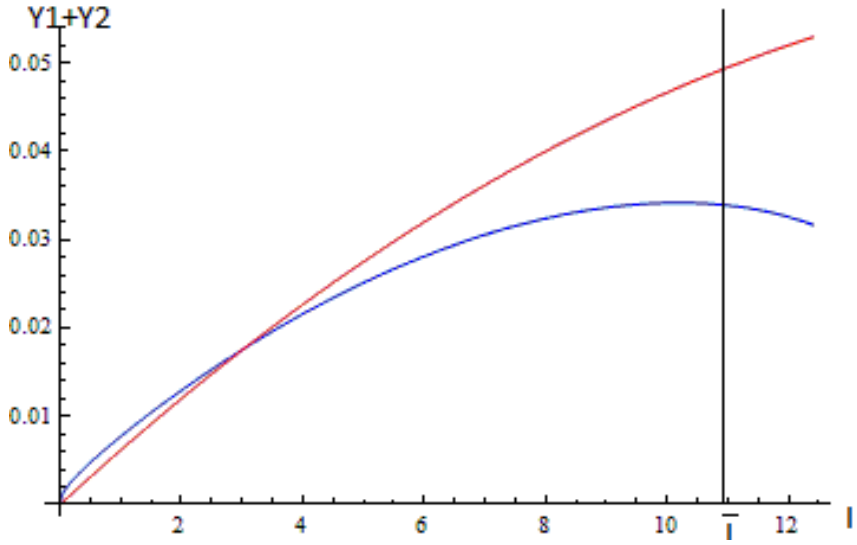
Introducing aquaculture leads in the long run to:
(i) a smaller total effort devoted to fishing;
(ii) a higher stock of edible wild fish and a lower price iff $d_1 < \overline{d}_1 = b_3 \frac{q_1}{\gamma q_3}$, *and vice versa, and a lower feed fish stock in all events;*
(iii) a higher total wild fish stock iff $\frac{b_1+d_1}{q_1} < \frac{b_3+d_3}{\gamma q_3}$, *and vice versa;*
(iv) an ambiguous effect on wild fish consumption when $d_1 < \overline{d}_1$, *a decrease of wild fish consumption when* $d_1 > \overline{d}_1$, *and an ambiguous effect on total fish consumption in all events;*
(v) a higher utility when $d_1 \leq \overline{d}_1$, *but a possibly negative effect on utility when* $d_1 > \overline{d}_1$.

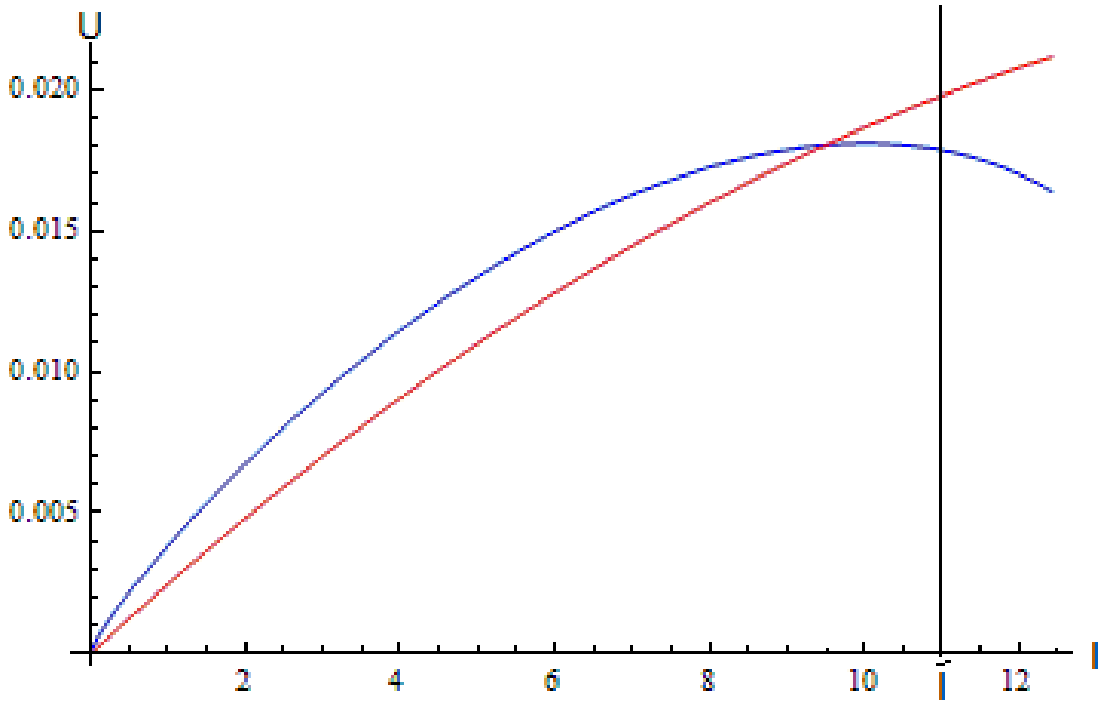
Moderate biological interactions: $d_1 < \overline{d}_1$	**Strong biological interactions:** $d_1 > \overline{d}_1$
$\widehat{E}_1 + \widehat{E}_3 < E_1^*$	$\widehat{E}_1 + \widehat{E}_3 < E_1^*$
$\widehat{X}_1 > X_1^*$	$\widehat{X}_1 < X_1^*$
$\widehat{P}_1 < P_1^*$	$\widehat{P}_1 > P_1^*$
$\widehat{X}_1 + \widehat{X}_3 \begin{cases} > X_1^* + X_3^* \text{ if } \frac{b_1+d_1}{q_1} < \frac{b_3+d_3}{\gamma q_3} \\ \leq X_1^* + X_3^* \text{ otherwise} \end{cases}$	$\widehat{X}_1 + \widehat{X}_3 < X_1^* + X_3^*$
$\widehat{Y}_1 \begin{cases} > Y_1^* = 0 \text{ when } I_w(d_1) < I < \overline{I} \\ ? Y_1^* \text{ otherwise} \end{cases}$	$\widehat{Y}_1 < Y_1^*$
$\widehat{U} > U^*$	$\widehat{U} ? U^*$

- Depending on the strength of biological interactions, the results change deeply.
  - When they are moderate, the consequences of the introduction of aquaculture are conform to intuition and to the results of the literature. The effects of market interactions dominate the effects of biological interactions.
  - When they are strong, the effects of biological interactions dominate those of market interactions. Aquaculture worsens the pressure on the wild edible fish stock, increases the price and reduces the consumption of wild fish, and has ambiguous effects on total fish consumption and utility.
- Consumers' utility may decrease even though more choice is offered to them because fishermen do not optimize ther behaviour (open access).

Illustration (strong biological interactions)







The role of consumer tastes

- Assumption: no biological interactions.
- Comparative statics exercise on k.

Proposition

Absent biological interactions,
(i) Long term stocks and efforts in the edible and the feed fish sectors evolve in opposite directions according to k.
(ii) For $\widehat{X}_1 < \frac{a_1/b_1}{2}$ and $\widehat{X}_3 < \frac{a_3/b_3}{2}$ and when preferences do not depend on k, the higher k the higher the edible fish stock and catch, the lower the feed fish stock and catch, and the lower the wild edible fish price. The effect of k on farmed fish production and price is ambiguous, but the value of production increases with k.
(iii) For $\widehat{X}_1 < \frac{a_1/b_1}{2}$ and $\widehat{X}_3 < \frac{a_3/b_3}{2}$ and when preferences do depend on k, the effects are completely reversed if the dislike of consumers for herbivorous farmed fish is sufficiently high.

- Initial steady state where both stocks are heavily exploited (only case where we obtain analytical results).
- Productivity effect: as k increases, fishing feed fish becomes more and more attractive because a same quantity may be transformed into more and more farmed fish.
- Preference effect: increasing k also means breeding fish that consumers like less.
- The second effect progressively dominates the first one.
- Numerical simulations show that
  - when preferences do not depend on k, utility is increasing in k due to the higher farmed fish production enabled by the better productivity of aquaculture, other things being equal;
  - when preferences depend on k, there exists a utility-maximizing farmed species type.

Conclusion

- Many hopes are placed in aquaculture.
- But we have shown that when biological interactions between the wild edible fish stock and the feed fish stock are strong, the introduction of aquaculture harms the wild edible fish stock and may harm consumer utility as well.
- In the good case where the introduction of aquaculture is beneficial, potential options in order to improve its sustainability:
  - Improving FIFO ratios through technological progress, by genetically modifying farmed species.
  - Finding a relevant substitute to feed fish.
  - Modifying consumer preferences? Further investigations needed to shed light on consumers' behavior towards farmed products.