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Modeling the global fishmeal and fish oil markets

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Abstract:

To explore the drivers of change in the complex system relating small pelagic fisheries and fishmeal/fish oil markets, to identify the interactions between these drivers and their overall impacts, we propose a bio-economic model, coupling the ecological and the economic dynamics of these global commodities. The model enables an analysis of the consequences of both global and local changes in the environment of production systems. Through sensitivity analysis of specific input parameters, we evaluate the robustness of the overall system to such changes and show that local responses of production systems and markets cannot be considered in isolation from the set of interactions at global level.

Keywords: Bio-economic modeling • networks economics • small pelagic fisheries • fishmeal • fish oil

1. Introduction

Small pelagic fisheries, anchovies, sardines, etc., represent about a third of the global wild marine catch. They constitute the first step of an industrial process that transforms fresh, bony fish of small size but generally rich in protein and high in fat content into two high quality products, meal and oil, both products being mostly used as key ingredients in specific animal feeds (Cf. appendix A). The link between the fisheries and the end-users goes through a series of steps that constitute an industrial and marketing chain covering the entire world as generally producing regions (mainly South America) are quite far away from the major consuming sectors (mainly Asia and Western Europe). Therefore, the industrial chain includes various steps such as processing, trading, logistics, transportation (fig. 1).

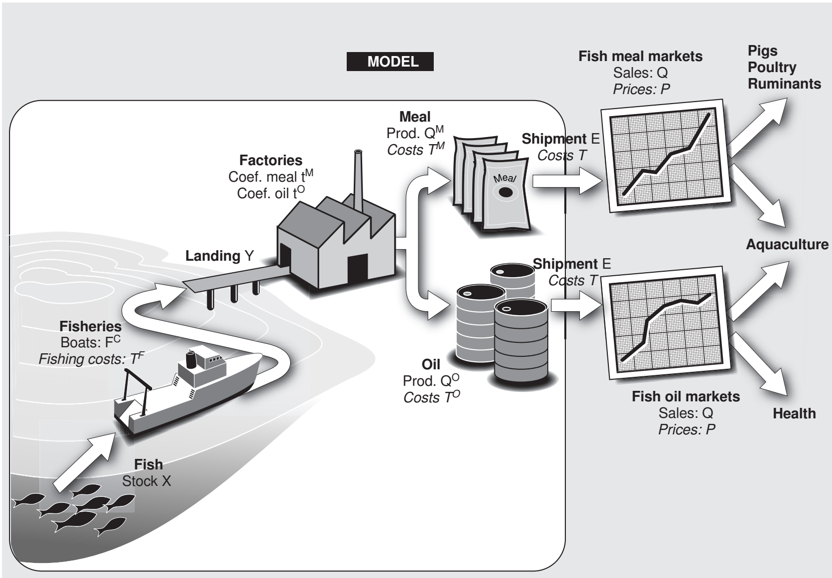

Figure 1. *Fish-meal and fish-oil markets and their supply chain*

A major feature of the system relating small pelagic fisheries and fishmeal / fish oil markets is the complex combination of a highly variable natural renewable resource, a modern, geographically diverse industrial processing structure, a worldwide commodity-based price sensitive market and highly selective and fully industrialized end-users, many of them located far away from the product source. Very little is known on how stocks of small pelagic fisheries are affected by external factors such as climate change (Hannesson et al. (2006), Lehodey et al. (2006)), increasing harvesting costs due to the growth in fuel oil prices, or demand growth on specific markets. Given the globalized nature of the markets on which fishmeal and fish oil are traded and the growing integration of large scale fisheries ventures worldwide (Garcia and Grainger (2005), Hannesson et al. (2006)), the consequences of such changes must be considered in the light of interactions between the different production systems throughout the world, which may either dampen or inflate the impacts of perturbations felt locally.

To illustrate and quantify the stakes of which this complex system is the subject, we have developed a specific supply-demand model. Such a model provides a framework to address issues regarding (1) the vulnerability of the small pelagic fisheries to both climate variability and change in the economic context in which fishmeal and fish oil are produced, particularly the increase in fuel oil prices and (2) the supply of fishmeal and fish oil markets in the context of a developing aquaculture demand from emerging economies and global price trends in food commodities. The goal of our model is to provide a tool to better understand the fish oil / fishmeal production/consumption system and more generally to ascertain what are the main processes of a worldwide market for a marine renewable resource.

The aim of fisheries simulation models (Grant et al. (1981), Isakson et al. (1982), Sparre and Willman (1993), Ulrich et al. (2002), Mardle and Pascoe (2002), Lleonart et al. (2003), Merino et al. (2007)) is to facilitate the analysis of the consequences and risks, both economic and ecological, associated to different scenarios regarding the co-evolution of fish stocks and fisheries subject to changing economic, environmental and management contexts. The model presented here differs mainly by the spatial scale to which the analysis is applied. Most of these models do not internalize different stocks' production into a global framework but into local markets, assuming these markets to be influenced by imports. Contrastively, this one aims to aggregate different small pelagic stocks exploitation into a single bio-economic model with two commodities on a global market. The model considers several stocks gathering small pelagic species, but no ecological interactions between them. It is the transformed production of landings from different stocks, which interacts with other stocks in a common global market.

In this model, world's small pelagic stocks are characterized by means of surplus production models (Schaefer (1954)) where the fishing mortality term depends on local management decisions. Producers vary their fishing capacity according to the profit they derive from fishing. Profits for each producer result from both the volume of production traded, the associated costs in terms of fishing, transformation and shipment, and the price at which production is sold. Price dynamics take into account the existence of financial externalities, with fishmeal and oil quantities sold on a common market determining each producer's sale price. The responses of producers in terms of investment in capacity, and in terms of fishing, determine the evolution of the exploited populations and the economic outcome of the activity.

The structure of the model developed to represent this system is detailed in Section 1. Section 2 presents the data used to calibrate the model and the scenarios tested. Section 3 presents the simulation results for these scenarios. Section 4 discusses these results and concludes.

2. Structure and equations of the model

Modeling choices. The system of small pelagic fisheries and fishmeal or fish oil markets is represented as an oligopolistic system with two commodities. This results in a network with a bi-layered structure with, on the side of supply, the set of production systems, from fish to fishmeal and fish oil, on the side of demand, the set of fish product markets, and the economic exchanges between them (fig. 2).

To represent the dynamics of the system, we have build a model that couples (1) the economic equilibrium between production systems selling on fish products markets, and (2) deterministic evolution rules for production systems and fish products markets. Thus the model considers two time scales.

On a short time scale (less than one year), each fishery in competition with other fisheries, determine how much to fish, where to sell according to the status of the fish stocks, to the intensity of demand; choices are computed as the equilibrium of the previous competition; to compute this equilibrium, we use the formalism of network economics (Nagurney (1993)), which provides a common framework to problems issued from spatial economics Samuelson (1952), game theory, migration

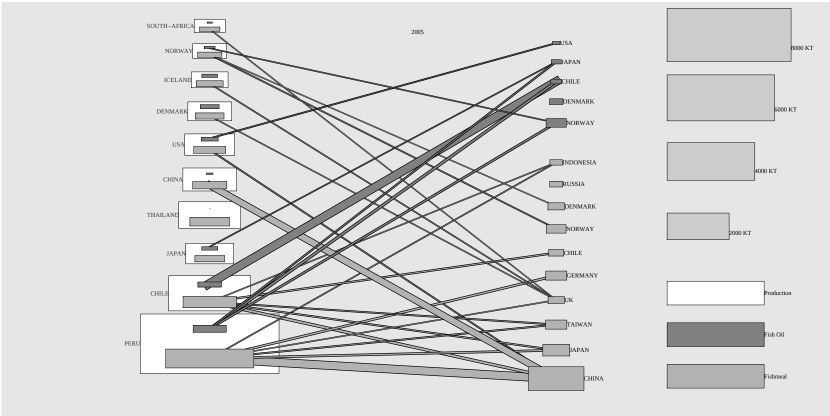

FIGURE 2. *Global network structure of the system: are represented, on the left part, fish catches, fish-meal and fish-oil production, on the right art, the fish-meal and fish-oil consumption; in the middle part, the arrows represent shipments. Size of boxes is proportional to volumes. Size of links is proportional to shipments. Remark the importance of Peru as a producer, of China as a consumer. These flows represent more than 70 % of total world trade of fihsmeal and fish oil.*

or traffic studies. It reveals being more adapted to the analysis of supply chains than conventional general equilibrium approach.

On a longer time scale, influenced by the choices of fisheries and the resulting incomes, fish stocks, fishing capacities and market demand all evolve in an exogenous manner.

All notations and equations of the model are resumed in tables 1 and 2.

Entities. According to a preliminary exploratory data analysis, entities of the model have been chosen as several national production systems and several national fish product markets. A production system is therefore a national structure that groups dedicated fleet and associated transformation factories. The model simplifies the players by using only the production and consumption systems that capture the majority of the trade. Peru, Chile, Japan, Thailand, China, USA, Denmark, Iceland, Norway, Morocco and South Africa are the main production systems, representing more than 70 % of the world production of small pelagic fish. Fishmeal markets in China, Japan, Taiwan, UK, Germany, Chile, Norway, Denmark, Russia, Indonesia, while fish oil markets in Norway, Denmark, Chile, Japan, USA, representing more than 80 % of the world fish product consumption are the consumption systems. This is according to the present state of the small pelagic and fishmeal and fish oil markets. It must be underlined that this system is characterized by the fast emergence of producers, such as Vietnam since the mid 1990s and Ecuador over the last decade, and recent consumers, such as Greece. To avoid overcomplexity, we have chosen not to consider these sudden structural changes in the present version of the model.

Summary of model notations and equations. Notations and equations of the model are summarized in tables 1 and 2.

TABLE 1. *Notations of the model. Top: characteristics of the competitive equilibrium. Bottom: characteristics of the dynamical system.*

Notation	Entities	Unit	Type
s	Production systems		
k	Fish products markets		
M	Set of fish-meal markets		
O	Set of fish-oil markets		
F_s	Fishing capacity of s	m^3	From dynamical model
U_s	Used fishing capacity (Effort) of s	m^3	Variable
X_s	Fish stock of s	ton	From dynamical model
q_s	Fish catchability of s	$ton^{-1}m^{-3}$	Fixed
Y_s	Landing of s	ton	Variable
Y_s^{quota}	TAC for s	ton	According to scenario
Y_s^{max}	Maximum landing of s	ton	Variable
c_s	Fishing costs per yield	Dollar / ton of fish	Constant
e_s	Fishing costs per unit of effective effort	Dollar / m^3	According to scenario
T_s^F	Fishing costs for s	Dollar/ ton of fish	Variable
T_s^M	Meal production costs for s	Dollar / ton of meal	Constant
T_s^O	Oil production costs for s	Dollar / ton of oil	Constant
T_{sk}	Shipment costs from s to k	Dollar ton of product	According to scenario
E_{sk}	Shipment from s to k	ton	Variable
τ_m	Technical production coefficient for meal	ton of fish / ton of meal	Constant
τ_o	Technical production coefficient for oil	ton of fish / ton of oil	Constant
Y_s	Fishing capacity	m^3	From equilibrium model
Y_s	Landings	t	From equilibrium model
E_{sk}	Shipments	t	From equilibrium model
P_k	Prices	Dollars	From equilibrium model
C_{sk}	Costs	Dollar	From equilibrium model
C_s	Carrying capacity	t	According to scenario
r_s	Renewal rate		According to scenario
i_s	Investment rate	%	According to scenario
j_s	Amortization rate	%	According to scenario
K_s	Capital costs	Dollar	According to scenario
v_s	Price of fishing unit	t	Constant
t_s	Capital remuneration rate	t	According to scenario

Notations.

Characterization of shipments. For all shipments between production system s and market k, we denote the shipped quantity E_{sk}. In the next paragraphs, we show how a given combination of shipments $E = (E_{sk})$ determines all other characteristics of the system, mainly costs and prices. This is the key point of the approach.

Characterization of markets. We use the symbol M for meal markets, O for oil markets. For all markets k, we denote P_k the unitary prices, Q_k the traded volume.

Characterization of production systems. Concerning the biological state of production system s, we denote X_s the stock , C_s the carrying capacity, r_s the renewal rate. To characterize the economic state of a production system s, we consider that every vessel has a capacity defined as the volume (m^3) of maximum catchable fish quantity per fishing trip (Ward et al. (1999), Pascoe et al. (1999)). Then the fishing capacity of a production system is the sum of the capacities of all its fishing vessels. We denote F_s the fishing capacity of production system s. If v_s denotes the value of an unit (m^3) of fishing capacity, then the capital of production system s is $K_s = v_sF_s$.

According to context, a production system may decide to use only a part of its fishing capacity; we denote U_s the used fishing capacity, i.e. the effective effort;

TABLE 2. *Equations of the model. Top: characteristics of the competitive equilibrium. Bottom: characteristics of the dynamical system.*

Equilbrium	**Equations**
Conservation equations	$Q_k = \sum_s E_{sk}$ $Q_s^M = \sum_{k\in M} E_{sk}$ $Q_s^O = \sum_{k\in O} E_{sk}$
Maximum landing	$Y_s^{max} = Min(q_s F_s X_s, Y_s^{quota})$
Production constraints	$\tau_m Q_s^M \leq Y_s^{max}$, $\tau_o Q_s^O \leq Y_s^{max}$
Yield equation	$Y_s = Max(Q_s^M \tau_m, Q_o^M \tau_o)$
Used fishing capacity	$U_s = Y_s/(q_s X_s)$
Fishing costs as a function of stock	$T_s^F = c_s + e_s/(q_s X_s)$
Fishing, production and shipment costs	$C_{sk} = T_s^M + T_s^F Y_s \tau^M/(\tau^M Q_s^M + \tau^O Q_s^O) + T_{sk}$ for $s \in M$ $C_{sk} = T_s^O + T_s^F Y_s \tau^O/(\tau^M Q_s^M + \tau^O Q_s^O) + T_{sk}$ for $s \in O$.
Prices	$P_k = a_k - b_k Q_k$
Functional relationship	$E = (E_{sk}) \to R = (R_{sk}) = (C_{sk} - P_k)$
Complementarity equation	$E^* = (E^*_{sk})$ with associated $R^* = (R^*_{sk})$ is an equilibrium if for all s there exists $\lambda_s^M \geq 0$, $\lambda_s^O \geq 0$ such that for all k : (1) for $k \in M$, $E^*_{sk} > 0 \Rightarrow R^*_{sk} + \lambda_s^M = 0$ and $E^*_{sk} = 0 \Rightarrow R^*_{sk} + \lambda_s^M \geq 0$ (2) $Q_s^{*M} < Y_s^{max}/\tau_m \Rightarrow \lambda_s^M = 0$; (3) for $k \in O$, $E^*_{sk} > 0 \Rightarrow R^*_{sk} + \lambda_s^O = 0$ and $E^*_{sk} = 0 \Rightarrow R^*_{sk} + \lambda_s^O \geq 0$ (4) $Q_s^{*O} < Y_s^{max}/\tau_o \Rightarrow \lambda_s^O = 0$;
Dynamics	**Equations**
Stock evolution	$X_s(t+1) = r_s X_s(t)(1 - X_s(t)/C_s) - Y_s(t)$
Profit definition Capital definition Capital costs definition Net profit definition Fishing capacity evolution	$I_s = \sum_k E_{sk}(P_k - C_{sk})$ $K_s = v_s F_s$ $t_s K_s$ $I_s - t_s K_s$ $F_s(t+1) = (1 - i_s t_s - j_s)F_s(t) + (i_s/v_s)I_s(t)$

overcapacity is a major issue of small pelagic fisheries Fréon et al. (2008). Our definition of fishing capacity is related to the concept of a frontier production function (Coelli et al. (2005)).

We denote the fishing costs T_s^F, the production costs T_s^M, T_s^O and production volumes Q_s^M and Q_s^O.

Economic equilibrium.

Balance equations. The traded volume is the sum of all shipped quantities:

$$Q_k = \sum_s E_{sk} \tag{1}$$

We assume that there is no storage, which is what is observed during last years, thus that production equals sales:

$$Q_s^M = \sum_{k\in M} E_{sk} \quad , \quad Q_s^O = \sum_{k\in O} E_{sk} \tag{2}$$

Getting yield and effort. We note τ_m , τ_o the technical transformation coefficients for meal and oil (the volume of fish needed to produce one ton of the commodity). We get yield assuming that there are no losses:

$$Y_s = Max(Q_s^M \tau_m, Q_o^M \tau_o) \tag{3}$$

Using a conventional relationship between yield Y_s, stock, effective effort and catchability: $Y_s = q_s X_s U_s$, we deduce the effective effort:

$$(4) \qquad U_s = Y_s/(q_s X_s)$$

Costs. For a product shipped on a path from a production system s to a market k, unitary costs C_{sk} are the sum of (1) costs due to the fishing process, (2) production costs assumed to be constant: T_s^M for meal, T_s^O for oil, (3) shipment costs assumed to be constant: T_{sk}.

Total fishing costs for a production system s are partly due due to effective effort, partly due to the amount of fish caught. We assume a linear relationship: $c_s Y_s + e_s U_s$ where coefficient c_s is the cost per ton of fish caught and e_s is the cost of using an unit of fishing capacity; as we have assumed that $Y_s = q_s U_s X_s$, we get the unitary fishing costs: $T_s^F = c_s + e_s/(q_s X_s)$.

Fishmeal and fish oil are two commodities extracted from the same product; one is an auxiliary product of the others; today there are countries producing meal without oil because lacking of a market; the inverse situation is possible in a next future. To compute the equilibrium and the choice of a producer to favor one commodity or the other, according to their selling prices and their production costs, we propose to allocate fishing costs to fishmeal or fish oil production according to ratios $\tau^M Q_s^M/(\tau^M Q_s^M + \tau^O Q_s^O)$ and $\tau^O Q_s^O/(\tau^M Q_s^M + \tau^O Q_s^O)$; with this simplification, if a commodity is not produced, it does not cost; if both commodities are produced at their maximum value ($\tau^M Q_s^M = \tau^O Q_s^O = Y_s$), corresponding ratios are 1/2; this simplification is justified by the fact that how production systems decide between meal and oil is not a crucial feature of the global system.

After some elementary algebraic manipulation, we get the expression of the unitary production and shipments costs on a path:

$$(5) \qquad C_{sk} = T_s^F Y_s \tau^M/(\tau^M Q_s^M + \tau^O Q_s^O) + T_s^M + T_{sk} \text{ for } k \in M$$

$$(6) \qquad C_{sk} = T_s^F Y_s \tau^O/(\tau^M Q_s^M + \tau^O Q_s^O) + T_s^O + T_{sk} \text{ for } k \in O$$

Inverse demand function. We base our representation of the short-term formation of first-sale prices on standard studies of this in fisheries (Garcia (2006), Ioannidis and Whitmarsh (1987), Gordon and Hanneson (1996), Nielsen (1999), Anderson (2003; 1980)). We assume that local producers are price takers, i.e. that they have no individual control on the overall supply of fish. For any given level of demand for their production, the overall volumes sold on the market will however define the levels of prices which will paid to individual producers in the different production systems. We have chosen to use a linear functional relationship relating prices to quantities:

$$(7) \qquad P_k = a_k - b_k Q_k.$$

Functional relationship. We have successively shown how shipments determine sales (equation 1), how shipments determine commodities production (equation 2), how commodities production determines yield (equation 3), how commodities production and yield determine costs (equations 5 and 6)), how sales determine market prices (equation 7). Thus, to a combination of shipments $E = (E_{sk})$, we may associate the combination $R = (R_{sk})$ where $R_{sk} = C_{sk} - P_k$ is the difference, for an unit of commodity, between production and transportation costs and market price. Using previous results and definitions, it is obvious that this a functional relationship $E \to R$. Let's remark that, due to the shape of equations 5 and 6, this relationship is non linear

Constraints equations. Not every combination of shipments is possible. There are several types of constraints affecting production. Firstly, catches are limited, either by a technical constraint, related to the fishing capacity: $Y_s \leq q_s F_s X_s$ where q_s is the catchability of fish in the ecosystem, or an administrative constraint, such as total allowable catches: $Y_s \leq Y_s^{quota}$. If there is no catch limitation, we put $Y_s^{quota} = \infty$. We have:

$$Y_s \quad \leq \quad Min(q_s F_s X_s, Y_s^{quota}) \tag{8}$$

Secondly, there are technical constraints related to the meal or oil processing:

$$\tau_m Q_s^M \leq Y_s^{max} \quad \text{and} \quad \tau_o Q_s^O \leq Y_s^{max} \tag{9}$$

We denote $\mathcal{H}$ the set of combinations of shipments $E = (E_{sk})$ such that $E_{sk} \geq 0$ and $Y_s \leq Y_s^{max}$ where Y_s is determined by equations 2 and 3.

Competitive equilibrium. A production system s increases its production Q_s^M and Q_s^O and its shipments E_{sk} until either (1) they are not profitable $R_{sk} = 0$, or (2) a production threshold has been reached $Q_s^M = \tau_m Y_s^{max}$ or $Q_s^O = \tau_o Y_s^{max}$. This encompasses the following mathematical definition of market equilibrium.

Definition *A feasible combination $E^* = (E^*_{sk}) \in \mathcal{H}$ with associated $R^* = (R^*_{sk})$ is an equilibrium if for all production system s there exists coefficients $\lambda_s^M \geq 0$, $\lambda_s^O \geq 0$ such that for all markets k two "complementarity" conditions hold:*

(1) *for a meal market $k \in M$, $R^*_{sk} + \lambda_s^M \geq 0$, and $E^*_{sk} > 0$ implies $R^*_{sk} + \lambda_s^M = 0$ and $E^*_{sk} = 0$ implies $R^*_{sk} + \lambda_s^M \geq 0$; moreover $\lambda_s^M = 0$ when $\tau_m Q_s^{*M} < Y_s^{max}$;*

(2) *for an oil market $k \in O$, $R^*_{sk} + \lambda_s^O \geq 0$ and $E^*_{sk} > 0$ implies $F^*_{sk} + \lambda_s^O = 0$ and $E^*_{sk} = 0$ implies $R^*_{sk} + \lambda_s^O \geq 0$; moreover $\lambda_s^O = 0$ when $\tau_o Q_s^{*O} < Y_s^{max}$.*

In this definition, λ_s^M (resp. λ_s^O) is the excess cost (shadow price) of production system s when producing fish-meal (resp. fish-oil). This definition means that, for a producer, advantages to sell on a market are the same for all effective markets; if this was not the case, the producer would have an advantage to sell more to the most advantageous of markets.

To analyze and compute the equilibrium set of this system, we use the formalism of network economics (Nagurney (1993)), which allows reformulating a supply-demand system in a general framework. Based on the "variational inequality theory", which is a generalization of convex programming, this approach determines in which conditions the equilibrium of an economic network exists and is computable.

We consider shipments E_{sk} satisfying $E_{sk} \geq 0$; we compute Y_s and Q_k according to balance equations. We denote $\mathcal{H}$ the set of shipments such that $Y_s \leq Y_s^{max}$. Then we have the following fundamental theorem:

Theorem 2.1. *A shipment combination $(E^*_{sk}) \in \mathcal{H}$ is an equilibrium as defined in paragraph 2 if and only if it satisfies the variational inequality*

$$\sum_{sk} R^*_{sk}(E_{sk} - E^*_{sk}) \geq 0 \tag{10}$$

for all shipments $E = (E_{sk}) \in \mathcal{H}$ *.*

We give the proof in appendix B. Then, we use a basic result of variational inequality theory.

Theorem 2.2. *There exists an equilibrium shipment*

Proof is application of Brouwer's fixed point theorem and is due to the facts that (1) $\mathcal{H}$ is a convex and compact subset of $\mathbb{R}^n$ and (2) F is continuous from $\mathbb{R}^n$ to $\mathbb{R}^n$ (Nagurney (1993)).

According to these results we may compute then equilibrium using one of the different algorithms defined in (Nagurney (1993)) and (Facchinei and Pang (2003)). We use the modified descent algorithm (Zhu and Marcotte (1993)), which reveals, in our context, being converging to a solution of the variational inequality.

Dynamics. The dynamics of the system are implemented according to the following recurrence mechanism. At time t, using (1) demand functions and (2) production costs and shipping costs functions, we solve the equilibrium equations, getting flows $E_{sk}(t)$, production $Q^M_s(t)$ and $Q^O_s(t)$, traded quantities Q_k, prices P_k and costs C_{sk}. Then, between time t and time $t+1$, we compute the new state of production systems: stock $X_s(t+1)$, and fishing capacity $F_s(t+1)$ and the new demand function of markets $a_k(t+1)$ and $b_k(t+1)$. This is detailed in the next paragraphs.

Investment dynamics. We assume an adaptive anticipations framework to represent investment behavior in production systems: investment at each time step is assumed to depend on anticipations regarding future profit by investors, which depend directly on the observation by them of past economic performance in a given production system. This is the background of many models representing fisheries investment behavior (Smith (1969)). We consider the special case where investors follow a myopic behavior, i.e. investment at each time step is a function of the performance observed for the production system at the previous time step. According to this assumption evolution of fishing capacity is related to investment depreciation.

A production system is characterized by fishing capacity F_s, capital $K_s = v_s F_s$, and profit $I_s = \sum_k E_{sk}(P_k - C_{sk})$. Capital costs are $K_s t_s$ with capital remuneration rate t_s. Net profit (that is taking account of capital costs) is $I_s - K_s t_s$. Then a fixed proportion of net profit $i_s(I_s - K_s t_s)$ is reinvested. The number of new units of fishing capacity is $i_s(I_s - K_s t_s)/v_s$. Depreciation is $j_s F_s$ with depreciation rate j_s. Finally, we get:

$$\begin{aligned} F_s(t+1) &= F_s(t) + i_s(I_s(t) - K_s(t))/v_s - j_s F_s(t) && (11) \\ &= (1 - i_s t_s - j_s)F_s(t) + (i_s/v_s)I_s(t) && (12) \end{aligned}$$

Stock dynamics. Evolution function of stock is a conventional production function with the renewal rate r_s, and the carrying capacity C_s:

$$X_s(t+1) = r_s X_s(t)(1 - X_s(t)/C_s) - Y_s(t) \tag{13}$$

3. Input and output of the model

Data. The model uses as input data quantitative characteristics of production systems, markets and shipping paths. Tables 3 and 4 describe the biological (renewal rate, carrying capacity, catchability, initial stock) and economical (fishing capacity, price of a fishing unit, fishing costs, transformation costs) characteristics of production systems. Table 5 describes fish product markets: average observed prices $\overline{P}_s$ and average observed volumes $\overline{Q}_s$ during 5 last years.

To build these tables, we have proceed as follows. From databases from the Food and Agriculture Organisation (FAO) and the International Fishmeal and Fish oil Organisation (IFFO), we have extracted (1) for all countries, data concerning catches Y_s, commodities (meal and oil) production Q_s^M, Q_s^O, commodities consumption, commodities flows E_{sk}; (2) for Peru, Chile, Norway, Denmark, Island, data concerning fishing capacity F_s and used fishing capacity U_s, fishing costs T_s^F, commodities production costs T_s^M and T_s^O; (3) data concerning observed prices P_k and volumes Q_k on the main fishmeal or fish oil markets. No inflation is considered in the model, which works on the basis of nominal values, as finding the right index for adjusting the different prices to real values does not seem straightforward. Although databases of the FAO go back to the 1950s, we have chosen the last five years to estimate the economical variables of the model. The advantages of this choice is that, although we do not take into account the effect of climate events such as the 1997 El Nino event, we have a reference baseline of relatively stable catches and prices, which we may consider relevant to the development of a robust modeling framework. For production systems s, when not available, the mean fish stock X_s, the carrying capacity K_s, the intrinsic growth rate r_s, the catchability q_s have been extrapolated in order to provide production stationarity: $X_s = K_s/2$, $Y_s = q_s X_s U_s = r_s X_s(1 - X_s/K_s)$.

Then, using these tables, other characteristics of the system have been obtained as follows. For production system s, fishing costs parameters have been estimated as $c_s = T_s^F/2$ and $e_s = q_s X_s T_s^F/2$. For market k, coefficients of the inverse demand function, a_k and b_k, have been estimated from observations, during the 2000-2005 period, of averaged prices $\overline{P}_k$ and quantities $\overline{P}_k$: $a_k = 2\overline{P}_k$, $b_k = \overline{Q}_k/\overline{P}_k$ (flexibility $-dP_k/dQ_k$ is 1 when market is in averaged state $\overline{P}_k$, $\overline{Q}_k$). For path $s \to k$, shipment costs C_{sk} (table 6) have been extrapolated in order to observe a network equilibrium, that is: if $E_{sk} > 0$ then $C_{sk} - P_k = 0$.

Building scenarios. Scenario building consists of making explicit assumptions about the underlying processes, setting the corresponding values to model parameters, and then interpret the results of the resultant simulation model. Concerning the production systems, we observe the dynamics of stocks, yield, fishing capacity, effective effort, profit, and concerning the markets, we observe volumes of exchanges and prices of commodities. Model parameters (endogenous variables) are given in table 7 with their default values, and how they affect a running simulation.

Impact of climate change. Scenarios about the impact of climate change (cf. table 7, part 1) consist of changing the values of production functions parameters: $r_s(t)$, $C_s(t)$. We usually consider the following scenarios (1) Climate change results in a uniform increase (or decrease) of renewal rates, assuming that it affects fish recruitment processes; (2) Climate change results in a uniform increase (or decrease) of carrying capacity, assuming that it affects the overall productivity of ecosystems. (3) Climate change results in a localized increase (or decrease) of carrying capacity, assuming that it affects the productivity of ecosystems in a different manner according to their latitudinal location.

Economic globalization. Building a scenario in terms of economic globalization consists of changing production and transportation costs (cf. table 7, part 2). We usually consider the following scenarios (1) Economic globalization affects shipment costs, for example through the increasing use of containers, or the increase of fuel prices, (2) Economic globalization results in increasing demand for forage fish

TABLE 3. *Characteristics of producers. The meaning of symbols is as follows. r is is the renewal rate, K the carrying capacity, X the initial stock. K and X values have been set in order to represent the past estimates of the stock, with an optimistic hypothesis of a maximum sustainable state ; then other parameters have been estimated in order to fit with past observed production (2000-2005 period).*

	r (no unit)	K (tons)	Catchability 10^6 (ton per m^3)	X (tons)
CHILE	1.000	10682000	13.9	5341000
CHINA	0.503	18952000	14.2	9476000
DENMARK	0.999	4098000	19.8	2049000
ICELAND	0.741	3703000	19.1	1851000
JAPAN	0.994	4018000	19.1	2009000
MOROCCO	0.976	1211000	35.9	605000
NORWAY	0.841	5002000	19.1	2501000
PERU	1.000	26306000	10.5	13153000
SOUTH AFRICA	0.558	4113000	23.9	2056000
THAILAND	0.070	9697000	24.8	4848000
USA	0.667	4153000	20.1	2076000
VIETNAM	0.593	1811000	34.6	905000

TABLE 4. *Characteristics of producers. FC is the fishing capacity, PFC the selling price of an unit of fishing capacity (per m^3), $Fish$ the fish yield, $Meal$ the meal production, Oil the oil production, FC the fishing costs, $PCMeal$ the meal transformation costs, $PCOil$ the oil transformation costs. These values have been estimated from IFFO data.*

	FC (m^3)	P FC \$ (per m^3)	Fish (tons)	Meal (tons)	Oil (tons)	FC \$ (per ton fish)	PC Meal \$ (per ton)	PC Oil \$ (per ton)
CHILE	50000	9600	3209000	817000	157000	63	120	200
CHINA	40000	2200	3000000	790000	0	70	110	160
DENMARK	25000	3600	981000	326000	105000	91	180	230
ICELAND	25000	5000	1100000	248000	80000	64	250	300
JAPAN	25000	4000	1111500	250000	64000	62	200	300
MOROCCO	10000	1600	135000	2700	0	50	80	160
NORWAY	20000	5000	1118000	219000	55000	84	250	300
PERU	150000	2000	8200000	1807000	321000	47	100	200
SOUTH AFRICA	10000	2400	524000	118000	4000	81	120	160
THAILAND	10000	1600	466000	397000	0	40	80	140
USA	18000	4400	930400	258000	92000	73	220	280
VIETNAM	7000	1400	153000	50000	0	50	70	100

Table 5. *Volumes and prices on different fish products markets (average on the 2000-2005 period). From IFFO.*

	price ($ per ton)	volume (tons)
MEAL		
CANADA	560	77000
CHILE	600	258000
CHINA	614	1900000
DENMARK	663	196000
ICELAND	900	60000
INDONESIA	579	88000
JAPAN	626	637000
MOROCCO	892	56000
NORWAY	688	268000
PERU	516	248000
SOUTH AFRICA	511	100000
TAIWAN	619	268000
UK	880	229000
USA	800	183000
VIETNAM	535	46000
OIL		
CHILE	650	207000
DENMARK	607	22000
JAPAN	568	118000
NORWAY	770	231000
PERU	544	40000
USA	1234	33000

Table 6. *Shipping costs between production systems and fish-meal or fish-oil markets. Shipping paths are determined from IFFO data. Shipping costs are related to distance but are adjusted to production costs in order the system converge towards an equilibrium with positive shipments on these paths.*

	CHI	CHI	DEN	ICE	JAP	MOR	NOR	PER	S.A	THA	USA	VIE
MEAL												
CANADA	.	.	.	.	.	.	.	.	.	.	75	.
CHILE	52	.	.	.	.	.	.	.	.	.	.	.
CHINA	288	56	.	.	.	233	.	285	.	.	190	73
DENMARK	.	.	.	.	.	.	52	.	239	.	.	.
ICELAND	.	.	.	39	.	.	.	.	.	.	.	.
INDONESIA	288	.	.	.	.	.	.	289	.	75	.	.
JAPAN	285	.	147	.	62	.	.	277	257	.	156	.
MOROCCO	.	.	.	.	.	62	.	.	.	.	.	.
PERU	.	.	.	.	.	.	.	77	.	.	.	.
NORWAY	.	.	.	.	.	.	61	.	.	.	.	.
SOUTH AFRICA	.	.	.	.	.	.	.	.	64	.	.	.
TAIWAN	282	.	179	.	.	.	.	277	252	.	174	.
UK	.	.	68	72	.	91	84	237	224	.	.	.
USA	.	.	.	146	.	.	.	161	.	.	98	.
VIETNAM	.	.	.	.	.	.	.	.	.	.	.	42
OIL												
CHILE	46	.	.	.	.	.	.	83	.	.	.	.
DENMARK	.	.	46	.	.	.	71	.	.	.	.	.
JAPAN	.	.	.	.	48	.	.	264	.	.	.	.
NORWAY	.	.	.	.	.	.	47	246	.	.	.	.
PERU	.	.	.	.	.	.	.	77	.	.	.	.
USA	.	.	.	.	.	.	.	.	.	.	114	.

products, (3) Economic globalization results in a localized (e.g. China) increase of demand for forage fish products, (4) Economic globalization affects capital behavior: more and more of profit is affected to capital remuneration, (5) Economic globalization affects investment behavior, (6) Economic globalization and competition result in technological change and increasing of catchability.

Sensitivity analysis. The objectives of a sensitivity analysis are to observe changes of the dynamics resulting from different values of one parameter. Practically, we perform sensitivity analysis of the behavior of the model in the following way: (1)

TABLE 7. *Parameters for scenarios (a) on the impact of climate change, top, (b) on the impact of economic globalization*

Climate change			
Parameter		V_0	Effect
Carrying capacity changes	a	0	Every year, carrying capacities C_s are multiplied by $(1+a)$
Renewal rate changes	b	0	Every year, renewal rates r_s are multiplied by $(1+b)$
Latitudinal climate changes	l	0	Every year, carrying capacity of a production system s at latitude lat_s, C_s, is multiplied by $(1+l(lat_s-40)/40)$
El Nino Event	e	0	For year 3 and 4, carrying capacity of a production in Peru and Chile is multiplied by $(1-e)$
Economic globalization			
Parameter		V_0	Effect
Demand changes (intercept)	cd	0	Every year, demand parameters (intercept) a_k are multiplied by $(1+cd)$
Demand changes (slope)	cs	0	Every year, demand parameters (slope) b_k are multiplied by $(1+cs)$
Growth of fish-meal markets	gm	0	Every year, for fish-meal markets k, demand parameters (intercept) a_k are multiplied by $(1+gm)$
Growth of Chinese demand	cd	0	Every year, on Chinese market k, demand parameters (intercept) a_k are multiplied by $(1+cd)$
Adaptation of fishing capacity	af	0.1	Reinvestment rate $i_s = af$
Capital remuneration rate	cr	0.1	Capital coefficients $t_s = cr$
Amortization rate	ar	0.1	Capital coefficients $t_s = ar$
Catchability changes	cc	0	Every year, catchability coefficients q_s are multiplied by $(1+cc)$
Total allowable catch	ta	1	Maximum of catches $Y_s^{max} = taC_s$
Fuel prices changes	pc	0	Every year, for all production systems s, fishing costs C_s are multiplied by $(1+0.8pc)$, for all paths, shipping costs C_{sk} are multiplied by $(1+0.2pc)$
Fishing rights	fr	0	Added to fishing costs
Importation taxes	it	0	Added to shipping costs on path ending in concerned country

select a "sensitive" parameter in the parameter listed in table 7, (2) set maximum and minimal values for this parameter, (3) set values for the other parameters according to some scenario whose sensitivity has to be tested, (4) set which variables of the system are to be observed, (5) run the model for 11 values of the selected parameter, regularly placed in the range (minimum, maximum).

4. RESULTS I : SCENARIOS

Uniform increase of carrying capacity scenario. Although climate change could both increase or decrease carrying capacity (Brander (2007)), for this exercise we assume that it has a positive effect on pelagic ecosystems and that it results in a regular 10% per year increase in carrying capacity , for all production systems. We present in figure 3 the kind of results we observe for all scenarios. In this particular one, fish stocks improve and consequently yields stabilize. Profit is increasing. With increasing supply and constant demand, there are less and less "borderline" countries. The decrease of fishing costs due to greater stocks, even if limited, allows all of them to gain more and more on the global market. However, our assumption of a myopic investment behavior is the cause of overcapacity increases. There is a low decrease of prices for fishmeal, significant for fish oil; when stocks are very high, production costs are mainly due to fixed costs; this is due to the cost function: $T_s^F = c_s + e_s/(q_sX_s)$; the nature of this function implies that high values of stocks X_s have an effect on prices which is less important than low values; this effect is higher for fish oil due to the higher transformation coefficient.

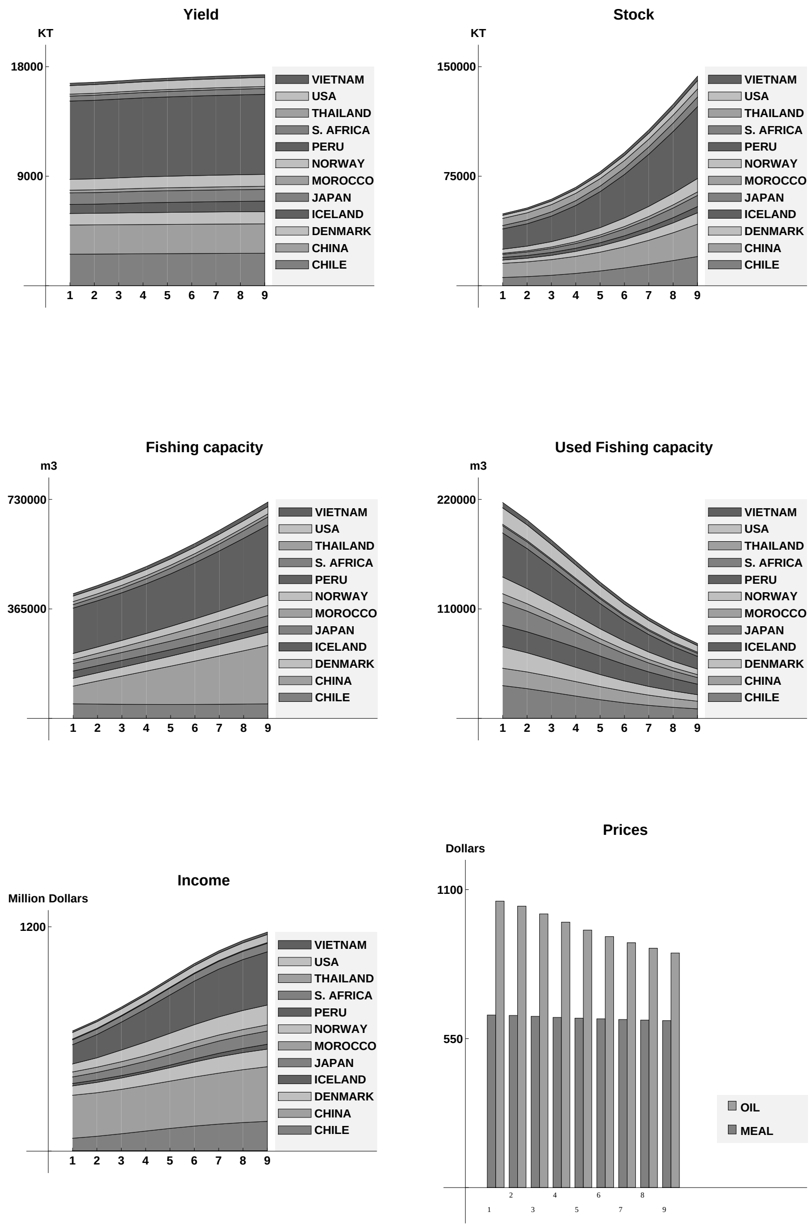

Figure 3. *Scenario of an uniform increase of carrying capacity. Every year there is a* 10% *increase of carrying capacity. Are represented, for all production systems, the fish yield (KTons); the fish stock (KT); the fishing capacity (m^3); the effective effort (m^3); the profit of the fishing sector (dollars); and the mean observed prices (dollars/ton)*

Increase in fuel price scenario. Second scenario is about how the system behaves when fuel prices increase by 5% per year, which is rather conservative, according to what has happened in recent years (figure 4). It has an effect both on fishing costs and shipping costs. At a given level of fuel prices, it is no more profitable to fish and thus boats are idled. The inefficiency of the fishery ensures that the smaller supply is not compensated by an increase in commodity price. The increase in production costs is limited, due to the necessity of taking into account fixed prices (capital costs). Profit decreases drastically in affected countries, and even though fishing capacity decreases overcapacity reaches a high level. This causes the collapse of several fisheries, (e.g. for example, that of Peru highly affected by increase of transportation costs), a decrease in global supply to under 10 Mt, which is not enough to satisfy demand. Decrease of yield results in a continued growth of stocks, underlying that collapse of fisheries are not due only to collapses of stocks. This process will continue until a level equivalent to the carrying capacity, in support of the idea that an increase of fuel prices would contribute to fisheries sustainability (Sumaila et al. (2008)). However, the collapse of fisheries would have catastrophic economic effects.

Global total allowable catches (TAC) scenario. Next scenario concerns the dynamics of the system under the assumption that catch limits are imposed for all ecosystems at a level of 5% of the estimated carrying capacity. This is a very conservative level compared to surplus production estimates (Jacobson et al. (2001)), which cannot reasonably be expected at the global level. We observe, in agreement with theory, a stabilization of stock, yield, profit and prices (cf. Supplementary material). Prices are 20 % higher than in the reference scenario, insuring high profit, and therefore high investment and thus overcapacity. In general terms this is similar to present conditions observed in Peru (Fréon et al. (2008)). This scenario suggest that in China, catch limits ensure a very high profit and increase in fishing capacity. However, a global fishmeal producing fish yield of 15 MT is too small to supply the fishmeal and fish oil demand, compared to the present yield 20 MT. Effects of this low supply on the development of aquaculture have to be analyzed. Indeed, what appears from these results is the efficiency of catch limits on an ecological and partly on an economic point of view: they insure high level of stocks and high profit to fisheries, but may result in an insufficient supply for markets.

5. Results II : Sensitivity analysis

El Nino. This first sensitivity analysis concerns the effects of an El Nino event as resulting in anchovy biomass drop rates $0\%, 8\%, 16\%, \ldots, 80\%$ in Peru and Chile during third and fourth year of simulation. In figure 5 are plotted the resulting values of yield, stock, fishing capacity, profit and prices. The level of stock recovery after an El Nino event determines two pathways. If the stock recovers (in biological terms), quickly exploitation and markets reach a level similar to the levels preceding the El Nino event. If recovery is delayed, fishing pressure is likely to remain high during the recovering period, and both exploitation levels and markets have to stabilize at a lower level than before the event. One may consider that this is a mechanism of shifting baseline (Pauly (1995), Pinnegar and Engelhard (2008)), which on a long term endangers the global production system.

Uniform increase of demand. A second sensitivity analysis concerns the effects of a constant demand increase of 0 % to 5 % per year. This last yearly increase represents an increase of 62 % at the end of a 10 years period. We observe (cf.

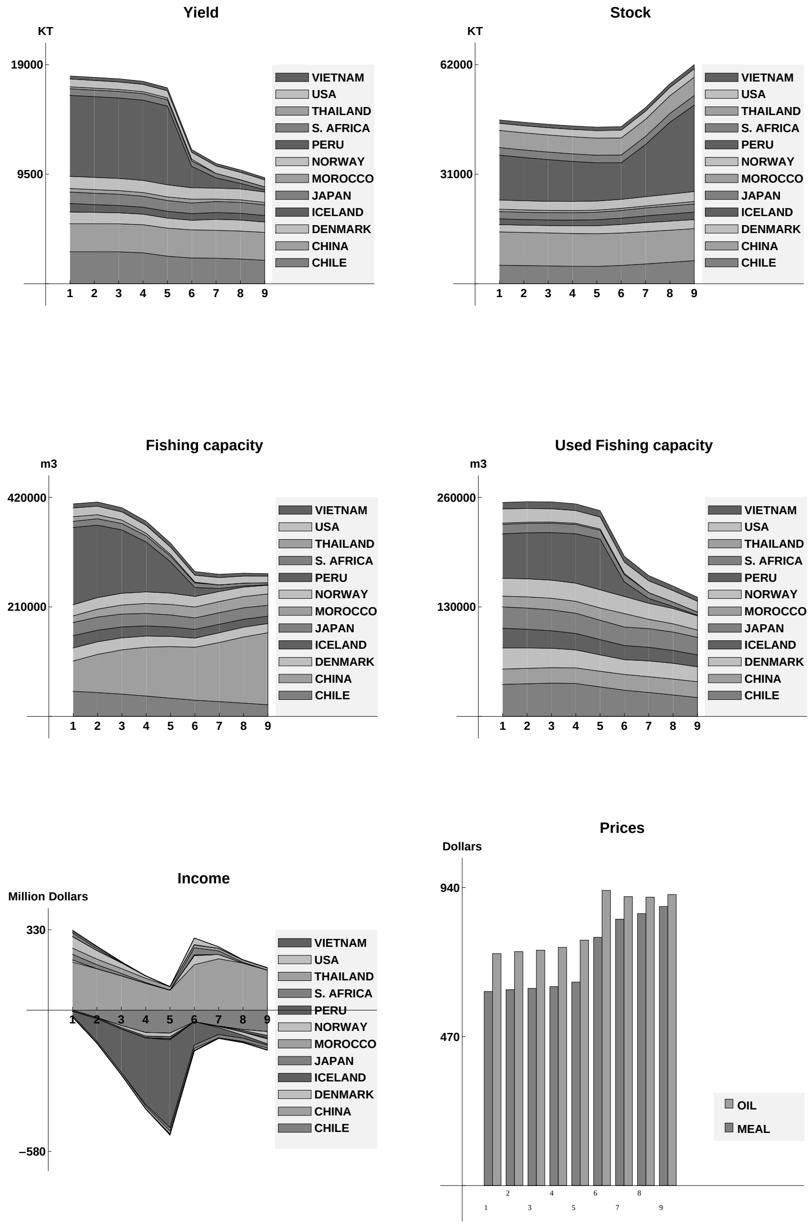

FIGURE 4. *Scenario of a regular increase of fuel prices. Every year there is a* 10% *increase of fuel prices*

Supplementary material) that the rate of demand growth has a huge impact on prices, profit, investment and overcapacity. Decrease of stocks is smooth, but at the end they reach a level at which exploitation is no more profitable. The dynamics of yield presents a plateau effect, which is a dangerous situation: observing only yield may conceal that stocks are endangered (Mullon et al. (2005)). This has to be related to the lack of concurrency on the fishmeal market, much dominated by the

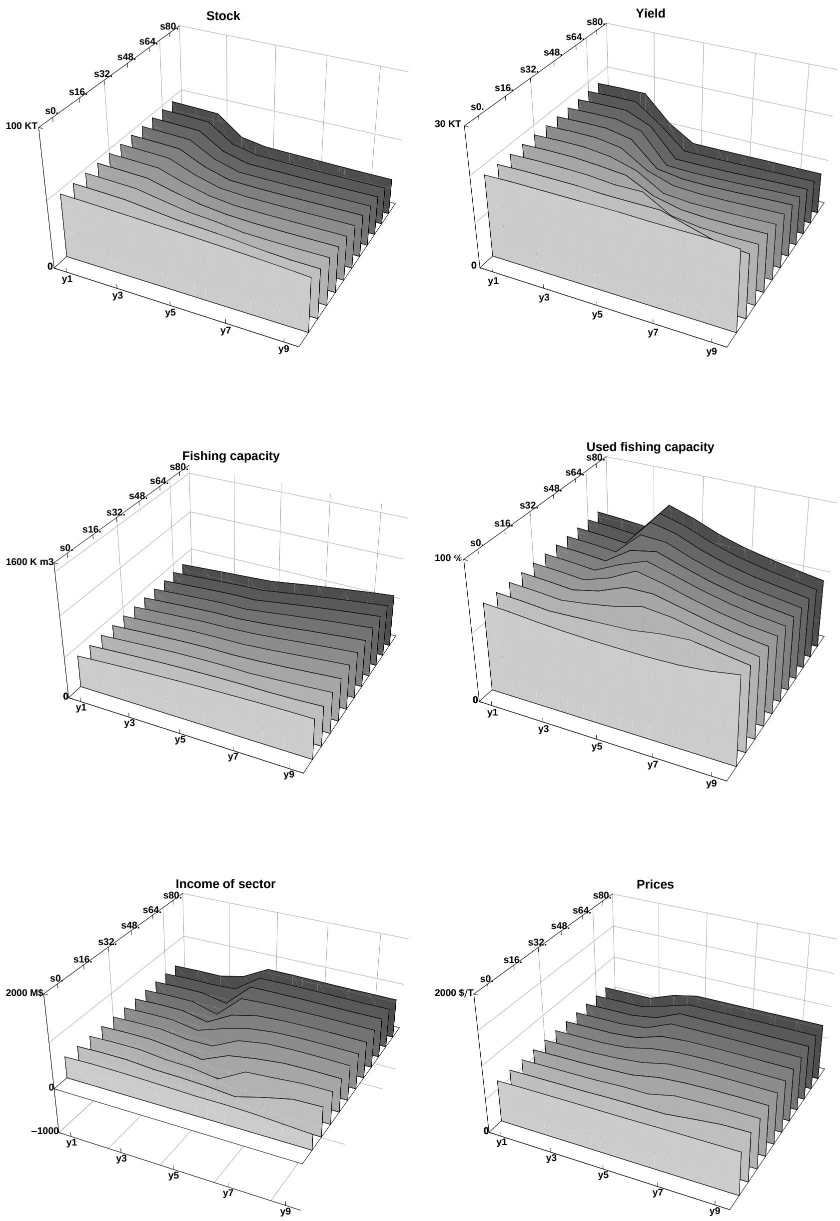

FIGURE 5. *Sensitivity analysis: impact of El Nino events. In each graph, a slice corresponds to an intensity of El Nino:* $s16$ *to a drop of* 16% *of stock in Peru and Chile during year 3 and 4. A slice represents the dynamics of a characteristics of the system during years* $y1, \ldots, y10$.

Peruvian production system, where producers are de facto limiting their supply. With this control, they get a higher profit and, according to the myopic investment behavior, have a tendency to invest too much, whence overcapacity.

Total allowable catches (TAC). Preliminary studies (Jacobson et al. (2001)) have estimated that the average exploitation of anchovy stocks can be estimated at approximately 8.5 % of carrying capacity and sardine at 5 % of carrying capacity, based on their average surplus production. In this sensitivity analysis, we vary the level of TAC successively from 5 % to 45 % of carrying capacity. In all cases (cf. Supplementary material), we observe that a TAC limit stabilizes the stock and the profit from its exploitation. As expected, high levels of TAC result in over exploitation and price drops, while low levels of TAC result in high prices and overcapacity. There is an optimal profit value at TAC levels of around 12 % of pristine biomass, with particular effects at the fishing behavior level. It appears in considering fishing capacity and effective effort graphs that at such optimal exploitation levels there is an encouragement to increase investment, increase in total (but not necessarily used) fishing capacity, with an inexorable decrease in global profit.

6. Discussion

Our objective was to develop a model, which would allow exploring the importance of interactions between regional fisheries, their regional and global markets and global production capital, in assessing the impacts of exogenous perturbations on local fisheries systems. The context of the analysis is a renewable resource, characterized by a highly variable supply and a strongly increasing demand for the commodities it produces. The emphasis of the analysis is on representing the full set of interactions between different production systems, and on analyzing the impacts of assumptions made regarding these interactions on the simulated dynamics.

To develop the model, we have followed a Pattern Oriented Modeling approach (Grimm et al. (2005)): the model has been designed to reproduce several identified dynamics, such as shifts, cascades or collapses, operating on both economical and ecological levels; this leads to the choices of a limited set entities and time resolution (10 years with 1-year steps); this leads to test the model on the basis of sensitivity analyzes of the dynamics to several parameters, before being used to develop scenarios of climate change, globalization, etc.

Most important modeling choices we have done are: (1) from an economical point of view, to consider the investment behavior as myopic and that landed volumes determine prices in a linear fashion, (2) from an ecological point of view, consider the system as mono specific, although it is difficult to envisage unique biological parameters for functional groups including short living and long living species, (3) from a modeling perspective, to represent the dynamics as resulting from the coupling of a market equilibrium process (annual balance between supply and demand determines trade and prices) with a dynamic deterministic process (present ecosystem state, fisheries, and trade determine next year's ecosystem state and fisheries.

Each scenarios tells us a different story, expressed as specific causality schemes. Due to the possible knowledge of all characteristics of entities during a simulation, it is possible to analyze results and conclude what mechanisms drive the systems. In every case, and for every scenario, there are ecological and economic explanations to the observed dynamics. Occasionally, the ecological and economic interpretation may sound paradoxical. For example, an increase of biological productivity results in decreasing profit, a decrease in stock size may result in an increasing exploitation, until a threshold value is reached, an increase of profit may result in capacity rises and thus in decreasing profit rates. Equally, there is an impact level of El Nino events beyond which the recovering slows down, which may sound a paradox for economists. Building such scenarios allows discussion in an interdisciplinary context, the main use of this model. It is important to realize, however, that due to the large number of uncontrolled exogenous variables, the capacity of this model for forecasting is limited.

If we consider the results concerning the effects of El Nino events with the ones concerning an increase of demand, we may hypothesize that there is certainly a threshold of increase of demand at which the system is not able to recover of severe El Nino events. If we consider these results with the ones concerning the implementation of TAC policies, we may hypothesize that specific regimes of TAC for Peru and Chile would ensure a better resistance of the system, and envisage its consequences about the structure of capital and profit. By this way, we derive the terms of new scenarios, of new sensitivity analysis. And we may put them at stake in the context of a global negotiation. This is the content of our present research and will detailed in a forthcoming paper.

From the many simulating experiences and sensitivity analysis we have realized, we would like to emphasize two specific conclusions.

Firstly, the global system in the last decades has been dominated by production from Peru, and an efficient TAC system there has stabilized small pelagic stocks. One could conclude that this stabilization of the dominant fishery may allow other countries to overexploit their resource, causing local collapses that may recover in the medium term without affecting the efficiency of global the system in any substantial manner. This dynamics have clearly been observed in our model simulations. However, one must underline that not all collapsed stocks have historically recovered in the medium term (e.g. Namibian sardine), and that the main weakness of the global system lies in the possibility of a climatically-driven collapse of the Peruvian stock combined with the present large overcapacity (Fréon et al. (2008)).

Secondly, the myopic investment behavior assumed in the model does provide a very simple explanation to fishing overcapacity (Fréon et al. (2008)). A TAC guaranties rents and encourages over investment. Do we fight over capacity or do we accept it just as a necessary negative effect of an ecologically-efficient management policy? Is overcapacity the result of an adaptation process to maximize profit during good periods, in anticipation of individual quotas being allocated based on present fishing capacity, while keeping options open should a drop in biological production require disinvestment? These are the kind of questions for which our modeling approach provides a mechanism and a formalism to explore.

It is important to note that this is not just a conceptual model but one where procedures for validation and calibration are considered. As a short term model, it is possible to relate model conclusions with actual events, which allows for practical validation. Our approach was based on defining reasonable values for model parameters from literature and data analysis, illustrating the functioning of the model with scenarios and sensitivity analyzes, and then interpreting the consequences as applied to the real system small pelagic fisheries and their products. This gives plausibility to our conclusions. For example, we underline that the importance of the increase of fuel prices on the stability of the system; we could also say that our assumptions concerning the decoupling of the fishmeal markets and the soya meal markets has been confirmed.

However, it is important to say that developing a short term model assumes some stability in its structural features, while it appears that these are evolving quickly. These elements advocate in favor of a more adaptive model, which is a real challenge for the future. As adaptations of the structure of the model, we should consider modeling the appearance or disappearance of new producers or consumers (for example, the development of the Vietnam fishmeal industry these two last years suggests that this country should be included in the model) or the changes of the connectivity of the network (for example due to the increase in the use of containers). We should also consider the potential ecological synchronies between anchovy and sardine, the substitution processes, the recycling of by-product of aquaculture, using more realistic costs functions (non linear) to represent effects of elasticities and cross elasticities, etc.

The global view of the model is proven very useful in an interdisciplinary context, making explicit messages across from ecologists to economics, reflecting on the importance of variability, of the differential renewal rates between stocks, and of carrying capacity on stock dynamics. It also allows feedback discussions from economist to ecologists on questions of elasticities, importance of price formation processes and investment behavior.

On a short term perspective, the model is adaptable to the socio-economic and political scenarios from the Intergovernmental Panel of Climate Change (Nakicenovic (2000)) and permits the quantitative evaluation of these scenarios; global change is not only described through the direct climate impacts on small pelagic populations (Chavez et al. (2003)) but through a pool of variables deciding future technological improvement trends, international cooperation or events such as substitution of fishmeal by soya meal in aquaculture. Even in the absence of an immediate crisis, frameworks such as the Millenium Assessment could be put forward to form the basis of international discussions regarding small pelagic fisheries management (Barange (2008)). This modeling approach could help to illustrate the major stakes of such discussions: the liability of the system for a global management, the identification of scales, agents, entities, levels of organization to be taken into account, the impact of factors such as the level of ecosystem variability, the evolution of the biomass, regulatory and macro-economic constraints, markets behavior, impacts of production growth.

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Appendix A. The system of small pelagic fisheries and fishmeal or fish oil markets

Fish is known to contain the highest level of natural proteins available in the world market, ranging from 64 % (on dry matter) to more than 70%, depending upon the species considered and the quality of the product. Dedication of small pelagic catches to fishmeal and fish oil production is related to the size of the resource available combined with the plant capacity available on-shore. Most of the resource processed into fishmeal and fish oil is caught within the 200-miles Economic Zone of the producing countries. In the last two decades the modernization of the fleets dedicated to small pelagic fish and improvements in handling and processing has increased the quality of landings, leading to a marked improvement in the conversion ratio.

Although very traditional for centuries in the northern countries of Europe, the fishmeal industry witnessed its real growth just after World War II, as it became the base of modern poultry feeding technique. Actually, the rapid growth of the poultry industry in the USA and, then, elsewhere in developed countries was a major booster to the fishmeal industry in the USA, based on Pacific sardines and Gulf menhaden, but also in Peru and Chile where it took over the more traditional guano industry (Leyton (2001)). Its spectacular and, to a certain extent, uncontrolled growth contributed to the major resource collapses in Peru in the early 70's, along the coast of California (Cisneros-Mata et al. (1995)), in Japan (Kawasaki (1993)). While the reasons for these collapses are debated, in the case of the Peruvian and Chilean anchovy fisheries it is now believed that a combinations of the effects of an El Nino event, a change of climatic regime and over-exploitation of an unregulated resource fishery caused the collapse (Alheit and Niquen (2004), Chavez et al. (2003)). Although the latter very lately recuperated, anchovy/sardine catches in Peru recovered quite well thanks to the high productivity of the Humboldt Current ecosystem combined with the very strict and responsive resource management policies developed by the Peruvian government during the 90's and implemented quite strictly in recent years.

Present fishmeal production and consumption trends are depicted in fig. 6; see also (Anderson (2003)). We note the importance of Peruvian and Chilean production, which represent more than 50 % of the worldwide production. Other important producers are Iceland, Norway and Denmark where capelin, blue whiting, herring, sprat and sand eel constitute the main raw materials for the fishmeal industry.

The main producers of fish oil are the same as of fishmeal. Nevertheless, the importance of Japan and Iceland as fish oil producers must ne noted (fig. 6). International fish oil trade is less intense than for fishmeal, with many countries, e.g. Japan, Chile, USA, consuming most of their production.

Since 1990, aside from weather related production shortfalls (e.a. 2003), worldwide fishmeal production has been generally rather stable with a slight perception of a decline. However, this does not preclude the general conclusion that this stability lies on the efficiency of the fisheries management policies, mainly in Peru and Chile, to sustain catches (Sanchirico and Wilen (2007)).

Stakes: On the supply side. Worldwide catches of the species which are mainly dedicated to fishmeal and fish oil production are depicted in figure 7. In recent

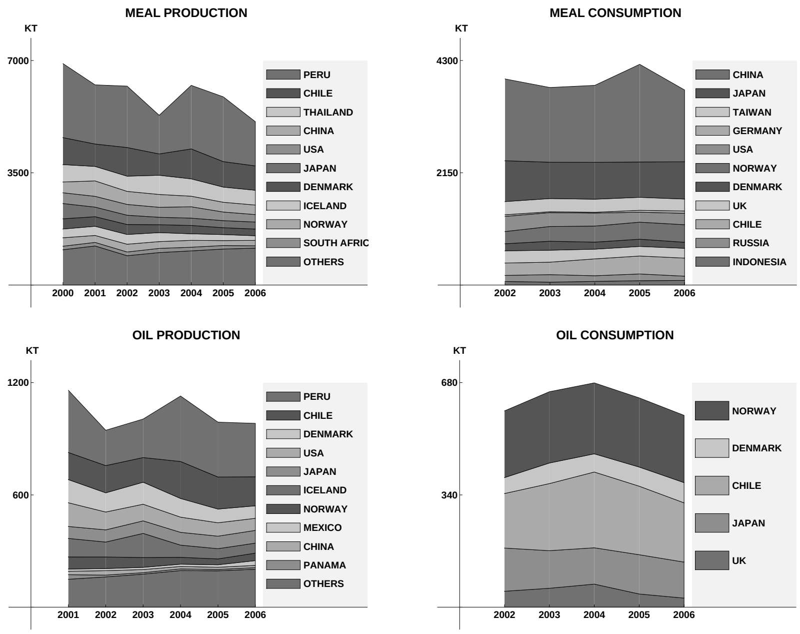

Figure 6. *Top, left: Fish-meal production (from IFFO). Remind the transformation coefficient* $\simeq 5$ *between fish and fish-meal. Top, right: Fish-meal consumption (from IFFO). Differences with previous figure due to the category Other countries, not represented here. Bottom, left: Fish-oil production (from IFFO). Remind the transformation coefficient* $\simeq 20$ *between fish and fish-oil. Bottom, right : Fish-oil consumption (from IFFO).*

years, they have reached a level of about 30 Mt, representing more than a third of the world's marine fish catch. A variability pattern appears with "pseudo-cycles" for most production systems, alternated high and low production levels on approximately decadal time scales (Schwartzlose et al. (1999), Fréon et al. (2008)). The amplitude of this variability is high with an order of magnitude 10 between low level and high level of production for almost all countries, species, and marine areas.

Some authors have observed synchronies between these pseudo-cycles of sardine and anchovy catches (Schwartzlose et al. (1999), Alheit and Niquen (2004)) : (1) sardine and anchovy populations tend to be out of synchrony in most areas e.g. if sardine is abundant, anchovy is not (Schwartzlose et al. (1999), Barange et al. (1999), Coetzee et al. (2008)) ; (2) peak and troughs in small pelagic are sometimes synchronic across systems, particularly in the Pacific (Lluch-Belda et al. (1992), Kawasaki (1993), Chavez et al. (2003), Hannesson et al. (2006)). However, the synchrony of these patterns has been questioned (Fréon et al. (2008)). As anchovies are mostly reduced to meal, while sardines are also canned for human consumption, the synchronies and associated substitution possibilities have important consequences for the fishmeal/oil production market.

Since the 1980s most of fisheries are regulated, mainly due to the institution of Exclusive Economic Zones. Practically all the major fishmeal industries are land

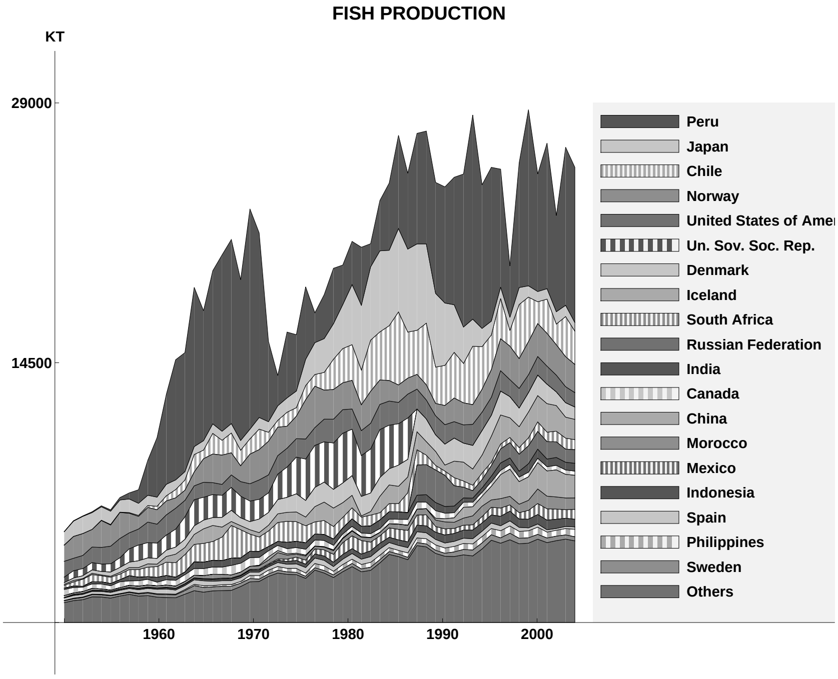

FIGURE 7. *Pelagic Production by countries(data issued from FAO Fishstat database). We have used the FAO category : Anchovies, Sardines, Herrings, plus Capelin, Sandeels and Blue Whiting.*

based, i.e. they are supplied by raw materials generally caught within the 200 miles economic zone. Therefore all major producing countries do have the ability to tighten their control on the fisheries through an adequate regulatory system. In some instances, landings are controlled by a third party inspection service allowing their immediate reporting.

However, overcapacity is an important consideration. In Peru, for example, the recovering of the stock following the 1975 collapse led to an increase in both the number of fishing vessels and their mean carrying capacity, disconnected with biomass trends (Fréon et al. (2008)).

Overcapacity is due to both the lack or inadequacy of access regulations and to changes in the demand and supply conditions, which may generate idle capacity when fishing conditions are not profitable.

Stakes: On the demand side. There has been a long-term slowly growing trend in prices of fishmeal and fish oil in the last decade (fig. 8a and fig. 8b), with particularly strong increases in prices observed in the last two years. This sharp increase relates to the speculative behavior of buyers in anticipation of a major El Nino event at the end of 2006, which did not materialize. The structural drivers of growth in prices relate to a regular increase of demand mainly for aquaculture (Asche and Tveteras (2004), Hardy and Tacon (2002), Kristofersson and Anderson (2006), Mente et al. (2006), Deutsch et al. (2007)) and, concerning fishmeal, a limited substitution by other meals.

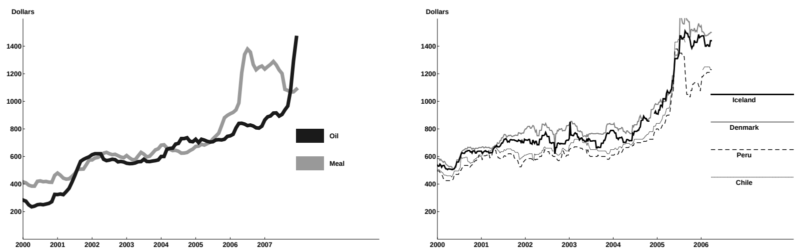

Figure 8. *Fish-meal and fish-oil prices (from IFFO). Complement with more recent data showing a stabilization at a slightly lower level. Fish-meal prices in several countries(from IFFO). Remark the connections between these prices. This justifies the approach : there is a worldwide market; observed differences are due to different shipping costs and local features of demand markets.*

Main substitute of fishmeal is soya meal. Substitution is the usual and only option for an end-user suddenly faced with a scarce commodity which price is rising accordingly. In the case of fishmeal, substitution is operating towards other sources of protein, mainly vegetal proteins such as soybean meal but also corn-gluten-feed, DDGS, the by-product of the ethanol industry when processed from corn. In the past decades, synthetic amino acids have also been used as partial substitutes to fishmeal although their use has been limited by their high price. More recently, the development of aquaculture, particularly of carnivorous fish species such as salmon has led to new opportunities for fishmeal usage, particularly for the higher qualities that the modernized fishmeal industry was able to supply. Thus, the substitution process is based on a complex balance between quality and/or specifications on one hand and price. In the 1980's and early 1990's, substitution was made only on a protein basis: a usual price ratio with soybean meal was in a range of 1.8 and 2.0, corresponding to the protein differential between fishmeal, around 65 %, and soybean meal, around 44 %. Starting in the late 90's/early 2000's, this price ratio rose progressively to another range of equilibrium between 2.8 and 3.1, reflecting the additional advantages offered by fishmeal (nutritional values and oil content). In recent years, the ratio stabilized to a new range of 4.2/4.8 reflecting the disconnection between the two markets (Anderson (2003), Kristofersson and Anderson (2006)). Fishmeal is becoming a specialty ingredient market following its own market logic.

On the fish oil side, rape oil is frequently considered the best substitute to fish oil in fish feed. A new price ratio with rape oil has developed over time on account of the presence of omega-3 fatty acids in both oils (Sargent (2007)). However, the recent developments of alternative bio-energy sources such as diester have completely modified the price relationship between fish and rape oils. Actually, the combination of rising fish feed demand and rising rape oil prices has led to a significant rise of fish oil prices. But progressively, fish oil has also become an important nutrient in both animal and human nutrition programs due to its beneficial health attributes. Here again, it is now clear that this market is moving into a specialty product niche market where price competition is not any more dominant but also linked to the nutritional benefits it will bring to a feed ration.

Appendix B. Solving variational inequalities. Proof of fundamental theorem

Theorem B.1. *A shipment combination $(E^*_{sk}) \in \mathcal{H}$ is an equilibrium as defined in paragraph 2 if and only if it satisfies the variational inequality*

$$\sum_{sk} R^*_{sk}(E_{sk} - E^*_{sk}) \geq 0 \tag{14}$$

for all shipments $S = (E_{sk}) \in \mathcal{H}$.

Proof: Put $L^M_s = Y^{max}_s/\tau_m$ and $L^O_s = Y^{max}_s/\tau_o$.

(1) if part: suppose that $(E^*_{sk}) \in \mathcal{H}$ is an equilibrium; put $I = \{(sk) \mid E^*_{sk} > 0\}$. We have:

$$\begin{aligned}
\sum_{sk} R^*_{sk}(E_{sk} - E^*_{sk}) &= \sum_{(sk)\in I} R^*_{sk}(E_{sk} - E^*_{sk}) + \sum_{(sk)\notin I} R^*_{sk}(E_{sk} - E^*_{sk}) \\
&= -\sum_{(sk)\in I, k\in M} \lambda^M_s(E_{sk} - E^*_{sk}) - \sum_{(sk)\in I, k\in O} \lambda^O_s(E_{sk} - E^*_{sk}) \\
&\quad + \sum_{(sk)\notin I} R^*_{sk}E_{sk} \\
&\geq -\sum_{(sk)\in I, k\in M} \lambda^M_s(E_{sk} - E^*_{sk}) - \sum_{(sk)\in I, k\in O} \lambda^O_s(E_{sk} - E^*_{sk}) \\
&\quad - \sum_{(sk)\notin I, k\in M} \lambda^M_s E_{sk} - \sum_{(sk)\notin I, k\in O} \lambda^O_s E_{sk}
\end{aligned}$$

because $E_{sk} \geq 0$ and $R^*_{sk} \geq -\lambda^M_s$ if $k \in M$, $R^*_{sk} \geq -\lambda^O_s$ if $k \in O$. Thus:

$$\begin{aligned}
\sum_{sk} R^*_{sk}(E_{sk} - E^*_{sk}) &\geq \sum_{(sk)\in I, k\in M} \lambda^M_s E^*_{sk} - \sum_{(sk), k\in M} \lambda^M_s E_{sk} + \sum_{(sk)\in I, k\in O} \lambda^O_s E^*_{sk} - \sum_{(sk), k\in O} \lambda^O_s E_{sk} \\
&= \sum_s \lambda^M_s Q^{*M}_s - \sum_{(sk), k\in M} \lambda^M_s E_{sk} + \sum_s \lambda^O_s Q^{*O}_s - \sum_{(sk), k\in O} \lambda^O_s E_{sk}
\end{aligned}$$

by definition of I. Thus:

$$\begin{aligned}
\sum_{sk} R^*_{sk}(E_{sk} - E^*_{sk}) &\geq \sum_s \lambda^M_s Q^{*M}_s - \sum_s \lambda^M_s Q^M_s + \sum_s \lambda^O_s Q^{*O}_s - \sum_s \lambda^O_s Q^O_s \\
&= \sum_{s, Q^{*M}_s = L^M_s} \lambda^M_s Q^{*M}_s - \sum_{s, Q^{*M}_s = L^M_s} \lambda^M_s Q^M_s \\
&\quad + \sum_{s, Q^{*O}_s = L^O_s} \lambda^O_s Q^{*O}_s - \sum_{s, Q^{*O}_s = L^O_s} \lambda^O_s Q^O_s
\end{aligned}$$

because $\lambda^M_s = 0$ if $Q^{*O}_s < L^M_s$ and $\lambda^O_s = 0$ if $Q^{*O}_s < L^M_s$. Finally,

$$\begin{aligned}
\sum_{sk} R^*_{sk}(E_{sk} - E^*_{sk}) &\geq \sum_{s, Q^{*m}_s = L^M_s} \lambda^M_s (L^M_s - Q^M_s) + \sum_{s, Q^{*o}_s = L^O_s} \lambda^O_s (L^M_o - Q^O_s) \\
&\geq 0
\end{aligned}$$

because $\lambda_s^M \geq 0$, $\lambda_s^O \geq 0$and $Q_s^M \leq L_s^M$, $Q_s^O \leq L_s^O$. This proves the variational inequality.

(2) only if part: suppose that $E^* = (E_{sk}^*) \in \mathcal{H}$ satisfies the variational inequality $\sum_{sk} R_{sk}^*(E_{sk} - E_{sk}^*) \geq 0$ for all shipments $(E_{sk}) \in \mathcal{H}$. For a given pair sk, we consider shipment defined by $E_{s'k'} = E_{s'k'}^*$ whenever $(s'k') \neq (sk)$ and $E_{sk} = 0$. It is clear that $E \in \mathcal{H}$. According to variational inequality: $R_{sk}^*(-E_{sk}^*) \geq 0$. Thus $E_{sk}^* > 0 \Rightarrow R_{sk}^* \leq 0$. Let's now show that for two shipments sk and sl of the same product, for example fish-meal $(k \in M, l \in M)$, such that $E_{sk}^* > 0$ and $E_{sl}^* > 0$, we have $R_{sk}^* = R_{sl}^*$. We consider a state $S = (E_{sk}) \in \mathcal{H}$ such that $S_{s'k'} = E_{s'k'}^*$ whenever $(s'k') \neq (sk)$, $(s'k') \neq (sl)$, and $E_{sk} = E_{sk}^* - \epsilon$, $S_{sl} = E_{sl}^* + \epsilon$. As $Q_s^M = Q_s^{*m}$, $S \in \mathcal{H}$. But variational inequality results in: $R_{sk}^*(E_{sk} - E_{sk}^*) + R_{sl}^*(S_{sl} - E_{sl}^*) \geq 0$. That is $(R_{sk}^* - R_{sl}^*)\epsilon \geq 0$. As we can take $\epsilon > 0$ as well as $\epsilon < 0$, we get $R_{sk}^* = R_{sl}^*$. We note λ_p^M this common value. If $Q_s^{*M} < L_s^M$, for m, it is possible to consider a shipment $S \in \mathcal{H}$ defined by $S_{s'k'} = E_{s'k'}^*$ whenever $(s'k') \neq (sk)$ and $E_{sk} > E_{sk}^*$. We get $R_{sk}^* \geq 0$. That is $\lambda_s^M = 0$.