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Modélisation Bioéconomique des Pêcheries Thonières: Mise en place d'Aires Marines Protégées en Haute Mer de l'Océan Indien

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Jeanne Marie Rose FORTILUS

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Directeur :	Patrice GUILLOTREAU	-	Université de Nantes
Directeur :	Christian MULLON	-	IRD (EME)
Rapporteurs :	Olivier GUYADER	-	IFREMER (AMURE)
	Murat YILDIZOGLU	-	Université Bordeaux IV
Examinateurs :	Christian CHABOUD	-	IRD (EME)
	Thomas VALLÉE	-	Université de Nantes

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Abstract

In this current work, to introduce, the biological and economic stakes in the fishery management have been outlined, then the marines protected areas (MPAs) issues notably in high seas has been presented.

In its second part, the network structure of the bioeconomic system, from tuna stocks to markets, has been illustrated. It shows how to homogenize catch data extracted from Sardara database and markets data from Fishstat database taking into account the network structure drawn. A detailed analysis of data already homogenized is hence suggested.

In the last part, a bioeconomic model of the global chain is implemented. This model is based on the network equilibrium concept. The network considered is described as large scale because it includes about 1000 biological and economic links. The algorithms used to compute the network equilibrium are provided in appendix and the iterative process are made for several years. Indeed, this work is designed to develop and analyze different scenarios including the implementation of MPAs. Results of scenarios tested are then presented before concluding.

Keywords: Bioeconomic Modeling, Network Analysis, Tuna Fisheries, Tuna Markets, Global Commodity Chain

Résumé

En introduction de la thèse, j'expose tout d'abord les enjeux biologiques et économiques de la gestion des pêcheries, puis la problématique des aires marines protégées (AMPs), notamment en haute mer.

Dans une seconde partie, la description de la structure en réseau du système bioéconomique a été réalisée: des stocks jusqu'aux différents marchés. Je présente ensuite comment la prise en compte de cette structure m'a permis d'homogénéiser les données de captures issues de la base de données Sardara et celles de commerce issues de la base de données Fishstat. Je propose alors une analyse succincte des données homogénéisées.

Dans la dernière partie de la thèse, je développe un modèle bioéconomique de l'ensemble de la filière. Ce modèle est basé sur la notion d'équilibre de réseau lequel est reconnu comme de grande taille puis qu'il implique environ 1000 liens biologiques ou économiques. Les algorithmes que j'utilise pour le calcul de l'équilibre du réseau tout en itérant le principe sur plusieurs années sont fournis en annexe. Enfin, je montre que ce travail est capable de développer et d'analyser différents scénarii, de la mise en place d'AMPs au large, entre autres, dont les résultats sont analysés avant de conclure.

Mots clés: Modélisation bioéconomique, Analyse des Réseaux, Pêcheries Thonières, Marchés de Thons, Chaine Globale de Commodités.

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List of abbreviations

ALB	Albacore (*Thunnus alalunga*)
BET	Bigeye tuna (*Thunnus obesus*)
BFT	Bluefin tuna
SKJ	Skipjack (*Katsuwonus pelamis*)
YFT	Yellowfin tuna (*Thunnus albacares*)
AO	Atlantic Ocean
IO	Indian Ocean
PO	Pacific Ocean
ECA	Eastern Central Atlantic
ECP	Eastern Central Pacific
EI	Eastern Indian
NEA	Northeast Atlantic
NEP	Northeast Pacific
NWP	Northwest Pacific
SEA	Southeast Atlantic
SEP	Southeast Pacific
SWA	Southwest Atlantic
SWP	Southwest Pacific
WCA	Western Central Atlantic
WCP	Western Central Pacific
WI	Western Indian
FAO	Food and Agriculture Organization
IATTC	Inter-American Tropical Tuna Commission
ICCAT	International Commission for the Conservation of Atlantic Tunas
IOTC	Indian Ocean Tuna Commission
OECD	Economic Co-operation and Development
RFMO	Regional Fisheries Management Organization
WCPFC	Western and Central Pacific Fisheries Commission
ALB-FRE	Albacore fresh
ALB-FRO	Albacore frozen
BET-FRE	Bigeye tuna frozen
SKJ-FRO	Skipjack frozen
BFT-FRO	Bluefin tuna frozen
YFT-FRO	Yellowfin tuna frozen
TUN-FRE	Tuna fresh
TUN-FRO	Tuna frozen
ALB-PRE	Albacore prepared
SKJ-PRE	Skipjack prepared
TUN-PRE	Tuna prepared
ABMT	Area-Based Management Tools
EEZ	Economic Exclusive Zone
FF	Fresh or/and Frozen
GTCC	Global Tuna Commodity Chain
MPA	Marine Protected Areas
VI	Variational Inequality
LCM	Linear Complementarity problem
MEY	Maximum Economic Yield
MSY	Maximum Sustainable Yield

BRA	Brazil
CAN	Canada
COL	Columbia
ECU	Ecuador
ESP	Spain
FRA	France
GER	Germany
IDN	Indonesia
ITA	Italy
JPN	Japan
KOR	South Korea
MEX	Mexico
MAR	Morocco
NET	Netherlands
PHL	Philippines
SYC	Seychelles
THA	Thailand
TWN	Taiwan
UK	United Kingdom
USA	United States of America
VEN	Venezuela

Part I

Introduction

General introduction

0.1 Introduction

The worldwide exploitation of fishery resources exploitation is generally unsustainable (Pauly et al., 2002). Sea food consumption during the last fifty years has almost doubled (FAO, 2009). In the current globalization context, imports and exports of goods and services exchanged across countries increase more and more. At the same time, investments in marine resource extractions are also increasing. Projections concerning climate change effects show impacts on fishery resources as well as on the fishery economies (Sumaila et al., 2011). However, some marine species are more affected by these changes than others. Offshore large pelagic fishes like sharks, billfishes, and some species of the tunas group belong to this category where the overexploitation threatens their stocks surviving (Myers and Worm, 2003; Majkowski, 2007; Pala, 2009). Specifically for tuna, pressure exerted on these species over the last decade affects their resilience for the future (Fonteneau, 2007). Fishermen pressurize tuna stocks while tuna consumers put the squeeze on tuna markets. During the last two decades, tuna products are increasingly demanded and tuna consumers become more exigent. This period is particularly distinguished by the increasing world demand for fresh tuna and tuna for *Sashimi* markets (Catarci, 2004). Tuna products are supplied fresh, frozen, and prepared on the worldwide market. Both tuna fisheries and markets evolve in an geopolitical context where cooperation between countries are necessary (Reid et al., 2003). Tuna resources like all natural resources can not be considered or managed as any other economic goods. They are certainly scarce, but in addition, their production is made following a natural cycle, they are mobile species, they are distributed over the global ocean, and they constitute a common access good. As a result, managing tuna fisheries seems to benefit both stocks and markets (Sumaila and Huang, 2012). However, many traditional management tools used in coastal fisheries have failed. Managing highly migratory species beyond the Economic Exclusive Zones (EEZ) is more complex and certainly more subject to failure (Bjorndal et al., 2000). In order to reach an efficient management, i.e., a sustainable exploitation of tuna stocks, other non-traditional tools such as seasonal or spatial areas closures are promoted. Used as a complementary management tool, marine protected areas (MPAs) seem as an efficient measure for both conservation of fish stocks and management of fisheries (Sanchirico, 2000; Roberts et al., 2001; Hart, 2006; Dalton, 2010). Thinking about the conservation of tuna stocks raises the overarching issue of governance that is common to all fisheries in the world (Pauly et al., 2005)

0.2 Theoretical Framework

The theoretical basis of this current thesis takes root in diverse economic disciplines and schools of thought. From natural resources management to market analysis, this current section presents how this work seems to be linked to different facets in economics.

0.2.1 Natural resources economics

The traditional bioeconomic modeling applied to fisheries management makes links between a natural capital and an economic activity (Clark, 1985; Hannesson, 1993). The natural capital stock or the living resources are here represented by tuna species that evolve in the worldwide ocean. They constitute a high quantity of biomass living in the pelagic ecosystem, have in most cases a longer lifespan, and are all high migratory species and overlapping on exclusive economic zone and international waters. Tuna species are generally large in size and exploited mainly by commercial fisheries. They are targeted for their great economic value. They are sold through worldwide markets (Jeon et al., 2008; Jiménez-Toribio et al., 2010). Flows generated by tuna markets widely contribute to world economies through tuna products, employments, fees, fishing rights, royalties and so on (Hunt, 2003). The biological and economic components are primordial in all studies based on the bioeconomic approach and they are focused on the natural resources exploitation, for example, in fishery (Clark, 1985; Wilen, 1985; Anderson and Seijo, 2010)... and in forestry (Kallio and Alexander Moiseyev, 2006).

0.2.2 Spatial economics

Cournot (1838) formulated the first economic production model in which the market price is given by the confrontation between supply and demand. In this explicit model, firms try to maximize their profit by anticipating the production level of other firms. Based on Cournot's model, Samuelson (1952) solved the first spatial equilibrium problem established for competitive markets that exchange different commodities. The model that we have been developed is also situated in a profit maximizing cooperative context. Identifying several types of agents in the economic system allows the consideration for exchanges. From the spatial equilibrium, to deal with the exchange of several commodities by different agents, the **Walras' law** in the general equilibrium context is well appropriated to this work. The **Walras' law** hence stipulates: *there exists an economic exchange between two agents if and only if the demand fits the supply.* In that case, there exists an exchange price. When the quantity supplied exceeds the quantity demanded there exist no price formation. This law is greatly applied in this current work by making possible the solving of the network system of the tuna commodity chain in which many stakeholders intervene. The problem formulation in the sense of the **Walras' law** could be translated into a complementarity relationship defining indeed an equilibrium state.

0.2.3 Network economics

A network is characterized by two sets of elements: the nodes (vertices or points) that are the dynamical units defining the graph size and the links (edges or lines) which ensure the interaction between nodes (Boccaletti et al., 2006). The network theory or graph theory is more often applied in physics and engineering sciences for designing physical or tangible networks in the transportation, energy, and communication systems. This theory also got success in other disciplines: (1) biology with the structure of deoxyribonucleic acid (DNA), (2) sociology with the consideration of social networks as such Internet social networks (see Borgatti et al. (2009); Schweitzer et al. (2009)), (3) and obviously in economics through interregional trades, accounting, general equilibrium, industrial organization... (see Nagurney (1993)). Some economic problems illustrated in a network structure tried to bring responses to the minimization of the transportation cost (Nagurney, 1993). The minimization problem of the transportation cost is also related to the spatial economics. The question of transportation cost minimization has been posed by Cournot (1838) and Samuelson (1952). The latter referred to a network structure to explain the spatial price equilibrium on the market. The network applied to economics or network economics defines the objective of this current work. The global tuna supply chain is described through a network structure. Nodes are given by all biological and economic entities intervening in this chain (from producers to consumers) and links give exchange flows between these entities. The bioeconomic model of the tuna chain presented here is essentially based on characteristics of a network. Prices and production costs are tributary to nodes while the transportation costs are imputed to links.

0.2.4 Global commodity chains

The chain concept could be defined as a set of economic activities whose structures are sequential and interconnected (Lazzarini et al., 2001). Many other concepts related to chain are used in economics. The value chain or value adding chain are a key concept in industrial economics (see Porter (1985)). The value that refers to a pay-off for a firm frequently coincided to the *filière* concept. The latter is viewed as a system of agents that ensures production and distribution of goods and services for the satisfaction of a final demand. The chain approach analyzes here the dynamics of economic activities by determining a hierarchical relationship between agents (Henderson et al., 2002). As for all chain analysis, these concepts contribute to the tuna chain description. But the modeling of the tuna chain is intimately related to the *global commodity chain* (GCC) concept (Gibbon, 2001; Gereffi et al., 2001; Gereffi and Korzeniewicz, 1994). In Gereffi and Korzeniewicz (1994), the global commodity chain is so defined:

> *sets of interorganizational networks clustered around one commodity or product, linking households, enterprises, and states to one another within the world-economy. These networks are situationally specific, socially constructed, and locally integrated, underscoring the social embededness of economic organization* (Gereffi and Korzeniewicz, 1994).

The commodity chain has been approached in the global context of the small pelagic fisheries and the global fishmeal and fish oil markets (Mullon et al., 2009; Merino et al., 2010). It is considered here in the same context for the global tuna commodity chain (GTCC) extending from tuna stocks to tuna markets.

Indeed, the modeling approach developed throughout this present work follows the main stages for the modeling of complex systems as described in Grimm et al. (2006).

0.3 Objectives

The bioeconomic modeling process applied to the worldwide tuna fisheries allows for the definition of the overall objective of this current work consisting the modeling of the high seas marine protected areas targeting mobile species like tuna. More concretely, this current work points out many specific objectives that are described below:

- The supply chain analysis, as usual, is complicated because many agents at a different levels intervene. As a result, the network structure as well as the detailed analysis of the worldwide tuna supply chain constitute an important aim to achieve. Data analysis is the key point for this stage.

- From results of tuna data analysis, an applied model that depicts the worldwide tuna chain from tuna stocks to tuna markets is aimed to be implemented. Through a bioeconomic scenario-oriented model many scenarios are seemed important to be tested including MPAs.

- In order to better tackle the common property issue in fisheries, this work also points out the fisheries management. An important goal to achieve is the presentation of some management tools usually used in fisheries with a special focus on MPAs. With the same objective to understand how fishery could be well managed, challenges that face high seas resources are also analyzed.

- The presentation of simulation results from the specific scenario considering MPAs remains the final goal that this work carries on. Through the bioeconomic model previously developed, the analysis of both biological and economic impacts and /or benefits of the implementation of MPAs to the Indian ocean high seas seems to be tenable.

0.4 Hypothesis and research questions

The research questions, which are until then unanswered verily not yet tackle, convey the justification and the originality of this current work. We intend to respond to the following research questions:

- The GTCC belongs to the class of complex systems. Its analysis requires diverse components. Is it then possible to portray it in both simple and explicit structure? How could the global tuna chain shape a network structure? How to characterize this structure?

- If the GTCC could be described in a network structure, it would be then possible to implement an applied model. How does create a data-oriented model in which all components of the network structure of GTCC are included? Why not testing some scenarios using this simulation model?

- Implementing MPAs in the Indian Ocean high seas that aims to reduce pressures on tuna species is viewed as one possible scenario tested by the model. Is it economically efficient to close some part of the Indian Ocean to fishing? The economic efficiency is defined here by a minimum level of profit generated by the fishery activities.

0.5 The structure of the thesis

In order to achieve all the objectives previously described and to present results as simple as possible, this current work is divided into four main parts. The first one outlines traditional management tools usually considered in fishery by analyzing MPAs challenges with a brief review on its both biological and economic aspects and finally presents the governance issue for high seas resources. Then, a detailed description of the global tuna supply chain from tuna fisheries to the final consumption of tuna commodities is presented in the second part where several maps and graphs are drawn in order to in order to better analyze the global chain. The third part of the thesis develops the analytical tools to implement a bioeconomic model. In this part, the methodology followed for the fulfillment of the main objective of this work is highlighted as well as the way to calibrate the model. In the last part, the main results described in the form of scenarios tested are interpreted. Based on the bioeconomic model developed in the first part, scenarios tested such as: the implementation of MPAs to the Indian Ocean high seas, an increase of the oil price... are discussed in this part. Finally, we conclude with a large discussion about results and a critical view of the current work.

Part II

From the traditional fisheries management tools to marine protected areas

Chapter 1

Basis of the bioeconomic management tools in fishery

Contents

1.1 Introduction

Since fishing is an economic activity that may generate profits and the fishery resources could become scarce, the need to manage these resources has been deeply felt (Conrad and D., 2012). The management requires a structural organization to generate results. Fishing resources are mobile, hence their management is complex and requires many components. In addition, property rights for these resources is known as not always well-defined making their management a priori not feasible or impracticable. The objective of this chapter is to present the most common management tools used in fisheries by trying to discuss their efficiency. First, an overview about the fisheries management will be detailed, then, management tools that are classified into biological and economic measures will be developed, finally a discussion of fisheries management is done.

1.2 Overview on the fisheries management

1.2.1 The open access issue in fisheries

Fishing resources like many other natural resources are often free to use by all users. The open access (*res nullius*) is defined by the non-excludability of exploiters for the using of a resource. Here, it refers to pure open access without regulation. In that case, no entity or individual holds the exclusive rights to use the resource. For exhaustible resources which are incapable of being regenerated following a natural cycle, an overexploitation quickly leads to depletion. By the opposite to exhaustible resources, the renewable ones could be regenerated, but its unsustainable exploitation, in the open access case for example, could lead to the same results as the former. The first work that faced the problem of fisheries under open access regime was the Gordon (1954)'s one. Gordon established that, open access resources are well known for multiple biological and economic problems such as: excessive fishing fleets and effort, overexploited fish stocks, no profitability of fisheries system, low incomes, etc. The figure 1.1 displays a bieconomic analysis of a fishery. On the top, the fish stock or the biological component and down, the economic one with the fishing effort. This figure makes a comparison between the pure open access and the optimal management in fishery. The open access is seen here as noticeable for generating a little or no net economic benefits in fisheries because the fish stock at the open access equilibrium Xoa shows the lowest level while the corresponding fishing effort Eoa is at the highest level by comparison with managed fisheries (($Xoa \prec Xmey$) and ($Eoa \succ Emey$)), where $Xmey$ and $Emey$ are stock and fishing effort respectively, corresponding to the maximum economic yield (MEY). In this figure, the level of catches (H) determines the level of revenue (the price p times the harvest H)) and the level of effort characterizes the total fishing cost (cE). The open access, gives a lower revenue because biomass is low and the fishing effort cost is high, compared with a well-managed fishery that aims to reach the MEY. Comparing with the profit maximizing system or the rent-seeking regime Conrad and D. (2012), the open access fishery is also highly wasteful in term of both the net benefits obtainable and the biomass level (cf. 1.1).

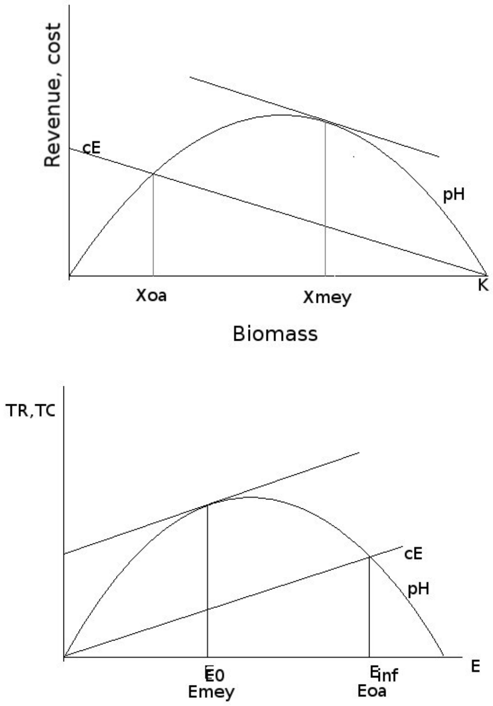


Figure 1.1: The open access (Xoa, Eoa) versus managed (Xmey, Emey) fisheries for fish stock and fishing effort

In order to improve income under the open access conditions, fishermen have to catch as fast and as much as possible as long as the fishing activity still generates some profits, i.e., a net benefit is obtained until reaching the maximum economic yield level. After this point, the remaining stock will be caught by others. In this situation, there is no incentive to preserve fish stock for the future. The stock will be inevitably depleted to what has been so called the tragedy of the commons (Hardin, 1968). It is generally admitted that open access arrangement of fish stock is wasteful, dangerous, inefficient, unsustainable, thence, the optimal management of fisheries is seen as necessary.

Managing a resource could mean restrain access to it or establish some specific conditions to get access on it. Establish some property rights of resources could simplify or make more efficient their management. Here are the most common types of property rights existent: the state rights, the common property rights, and the private rights.

- The state rights *(res publicae)* exist when individual may use the resource only according to the rules established by the state.
- The common property rights *(res communes)* gives to a specific number of individuals the rights to profit from the resource and to exclude those who are not members.
- The private property *(res privatae)* occurs when an individual, agent or firm holds the exclusivity to exploit, conserve, or sale the resource.

Among these main types of property rights, there exist some intermediary forms, for instance, the unregulated common property, in which individual can individually act according to its proper initiative, is not so different from open access in results. In other words, the existence of rights does not mean that they will resolve problems about the exploitation and possession of resources. In particular, it has often been difficult in the context of marine resource management to find a set of property rights that simultaneously satisfies stakeholders preconceived notion of resource access and optimizes exploitation levels of biological resources. The following section shows in details the real challenges existing in the management of such resources.

1.2.2 The stakes of fishery management

The objective of fishery management, in economic terms, *is to ensure that fishery capital asset makes the maximum economic contribution to society, through time.* Objectives aim by managing fishery resources could be diverse. Some management goals have been listed below:

- maximum employment,
- sustainability and responsibility in fisheries,

- conservation of fish stocks and the environment,
- generation of exports,
- economic efficiency
- food safety
- social equity

All of the above objectives could be linked and the real difference between them depends upon the management system that is enforced. According to Charles (2001, p. 70-71), The fishery management system is characterized by the following components:

- The fishery policy and planning refers to strategic management. It aims to fix all objectives, elaborate all policy directives, legislation, regulation in order to take decisions.
- The fishery management or the operational management intends to control management tools and measures in long and short term. This structure also acts to provide and collect all necessary information.
- The fishery development gets focus on the productivity, human system, and the physical dimensions of the management structure.
- The fishery research aims to conduct assessment, analyze, and understand the fishery system.

In this present work, the typology used by Arnason (2009) to describe the fishery management system has been drawn in figure 1.2 and followed all along the following sections.

1.3 Ecological/economic fisheries management

The fisheries management system is one of three components of fisheries management regime[1]. There exist different classes of tools used to manage fishery resources.

[1]it defines that a set of social prescriptions and procedures that control the fishing activities and includes (i) the fisheries management system, (ii) the monitoring, control and

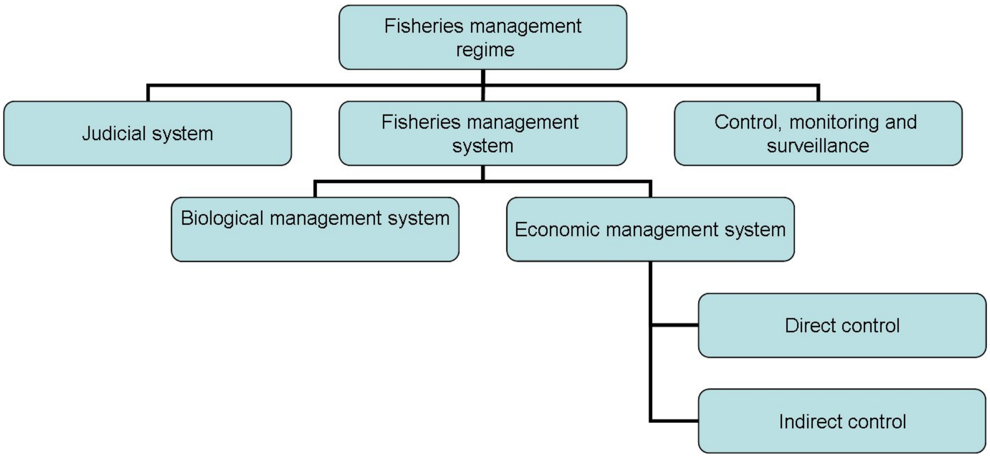


Figure 1.2: Fishery management systems
(source: Arnason (2009))

They range from biological to economic tools according to Arnason (2009)'s classification.

1.3.1 Biological tools

Biological fisheries management are all measures that act directly on biological components of fisheries and that may conserve and enhance the fish stock. For example, regulation of mesh size, total allowable catch (TAC), areas closures, nursery ground protection and the like. They respond essentially to biological problems. All of these measures act essentially on the fish stock and resume mainly to the control of the catch. All of them do not also act on selectivity of fishery (except TAC,e.g., selectivity on juveniles, bycatch...) However, although these management tools could limit the overexploitation of fish stocks but they are unable to solve the common property problem of the resources (Clark, 2007).

1.3.2 Economic fisheries management

Economic management in fishery could be defined as all management decisions that regard economic aspects in this activity. It includes direct and indirect economic management tools also called direct and indirect controls. Direct control is defined

surveillance and (iii) the fisheries judicial system) as all restrictions that affect directly the fishermen activity, while indirect control is all incentive measures that encourage fishermen to change their behavior.

Direct economic control imposes explicit constraints on fishing activities. Restrictions can apply directly on the fishing effort (days at sea, number of hooks, fishing time, number of vessels ect.) and/or on the fishing capacity (engine size, power maximal of vessels). Like the biological management systems, the direct economic control on fisheries activities fail to generate net economic benefits in the long run because common property problems remain also unresolved. By limiting the fishing capacity or the fishing effort to hedge free access problems, in the short run, fishery will be profitable (revenues exceed costs). The increasing profitability will encourage further investment and an incentive arise either for some exploiters to increase their effort or for new firms or fishermen to enter into fishery (as shown in the figure with an increasing fishing effort). If free access competition leads to depletion of fish stock, the direct control on both the fishing capacity and the fishing effort itself leads to increase investment and creates overcapacity in the long run. In terms of economic results, economic efficiency is achieved. *There exists an economic efficiency when the maximum output is produced for the inputs used, and inputs are allocated to minimize costs for any output level.*

Indirect economic measures are viewed like management tools that theoretically act directly on the common property problems. Indirect economic management of common property of fish stock might be viewed in two ways:

1. controlling its exploitation by public authorities through taxes (Pigou, 1920),

2. establishing private property rights of fish stock (Coase, 1960).

When fishery resources are controlled by public authorities, taxes are usually enforced. All measures through taxes must limit the overexploitation resulting from open access (Hannesson, 1993). In the private property rights system, owner of fishery resources has a strong incentive to limit fishing to whatever the level of fishing maximizing profits.

1.3.3 Indirect control I: tax or royalties on landings or effort

The taxation system is an incentive management tool implemented by the government. Enforcement of taxes in fisheries aims to internalize the social cost in the total fishing cost of industries. With taxes, this is also a way for fishing industries to squeeze externalities in their cost function. In this case, we talk about the Pigovian corrective taxation (Hannesson, 1975; Dasgupta, 1982). Indirect control with taxes can be applied on landings, the fishing effort, fishery inputs, etc. When taxes are applied on landings, revenues are reduced. Whereas when the fishing effort or the fishery inputs are taxed, the cost of fishing increases. If the taxation system avoids the common property problem, it cannot prevent the emergence of other problems in fisheries management such as social and technical problems. For example, tax on incomes disheartens the labor effort, tax on profits discourages investment and the same, tax on value-added disheartens both labor and investment. In other words, tax creates distortions and inefficiency in economy. However, tax could indubitably generates public profits and indirectly encourages resource conservation.

1.3.4 Indirect control II: property rights

As seen above, there exist many different kinds of property rights. They are important to consider for fishery resources as well as for all high supply goods (Demsetz, 1967). They are also important for trading and for the operation of the market system, while the existence of markets does not lead to the creation of property rights. The most common means to establish property rights in fishery are: the licenses, the sole ownership, the territorial use rights, the individual quotas, and the community rights.

1. Fishing licenses provide fishermen or industries right to conduct fishing. Like the previous problem when restrictions are made on catches, both the fishing effort and capital investment increase with licenses because license holders compete to share fisheries resources. For this reason, the license-based management is unable to remove common property problems from fishery resources.

2. A sole owner holds the capacity to eliminate common property problems because individuals or firms are the exclusive owners of resource. The fishery is managed like a private enterprise. In this case, the economy is fully efficient because the profit maximizing system is implemented. In comparison to both the open access and common property fishery where the fishery stock is under the optimal stock due to overexploitation (from society's point of view), in the sole ownership, the stock level is equal to the optimal steady state level (see Bjorndal et al. (2000)). The common property stock level could reach that of the sole ownership system if and only if the discounted rate is very low and tends to zero. The sole owner is known as being rational and the discount rate for the exploitation of fishery resources is high because exploiters are less impatient.

3. The territorial use rights in fisheries (TURFs) get the same principle than the sole ownership system. They are all both private management systems. For the TURFs, the rights are specifically gained because of the geographical situation of resource. The exploitation of certain areas of the ocean could be done by a single owner or a group of owners. They could exclude all other exploiters. These rights to exploit and to exclude could be or informally established (Branch et al., 2006). The economic results in this kind of property right regime are obviously highly efficient specially for sedentary fish stocks.

4. Individual quotas (IQs) define property rights in harvesting volume, and individual transferable quotas (ITQs) are individual quotas that are just transferable. IQs and ITQs are long considered by economists as the solution to inefficient fishery by restoring profitability. This kind of fisheries management tool based on property rights showed its limits. IQs and ITQs are both extraction rights and they represent an indirect property rights in the whole fishery resources and in their environment. The issue on the social efficiency of the ITQs is a real problem. The quota system is unable to remove alone common property problems because the individual-quotas holders get very little control over the fish stock and the entire marine environment (Arnason, 2005).

5. The community rights or share fishery system is a joint management system characterized by the exploitation of fishery resources by restricted number of harvesters. The community rights or community based management system found success in the case of subsistence fisheries but not only (Ostrom, 1990). These fisheries are usually marginalized and neglected by local governments whom their main preoccupation is fixed on the intensive industrial fisheries (King, 2007). The stakeholders of the community system can easily meet and take decisions on their fishing activity and create their own management tools.

1.4 Conclusion

From free access, to promote a management of fisheries resources requires a deep change. Free access or the absence of management is revealed dangerous (in the sense of the overexploitation) for the resources to exploit as well as for the exploiters. Management in general has never been easy. For fisheries, that are complex resources because they deal globally with fish species that are mobile and in which property rights are not well defined, fisheries management serves first to regulate the access to the fishery before implementing conservation and effort limitation measures. In this chapter, different types of management tools have been showed including biological components or economic aspects in fisheries. The efficiency of each tool has been also discussed. The great question about the choice to manage remains in the management cost and who bears it (Arnason et al., 2000).

Fisheries management is generally costly (scientific advice, monitoring, enforcement costs, judicial costs...). Note that ITQs systems are not designed to remove the non-excludability problem of fishery resources. Due to the problems of inadequate information, inappropriate incentives, and misalignment of costs and benefits, the government is generally an inefficient provider of fisheries management services. Hence, private management or fisheries management by ITQs holders could be promoted. However, shifting from an inefficient to a more efficient management requires costs of negotiating, defining, and enforcing rights (Coase, 1960). For group-based management systems, for example, the transaction costs are high. The management costs are also greatly dependent on the value of the resource and include both private and social costs. When the resource rents are dissipated, in the open access case, the social cost imposed is obviously high. The final conclusion is that private management (via IQs and ITQs) and public management (via taxes) are both able to act on the common access problem in fisheries and generate profits (Clark, 2007). However, the management way and its subsequent results are obviously different for the two types of systems. With the private management of resources, only an individual, a company, or a collective of individuals enjoy the fisheries profits. When a taxation system is enforced, the state or the public authority gets profits from tax collection that could be redistributed into the social services. About the social equity, the latter is more fairness whether corruption is absent. Finally, this current chapter get focus on traditional management tools trying to follow a classification. However, a key and a recent management tool generally used in fishery is intentionally omitted: the marine protected areas. Due to both the complexity of such tool and the importance attached to it inside this current work, the chapter that follows is dedicated to the discussion of MPAs.

CHAPTER 2

What is the challenge with marine protected areas implementation ?

Contents

2.1 Introduction

The term Marine Protected Areas (MPAs) refers to marine areas where special limitations are placed on human extractive activities. This term could be used in the context of habitat protection, biodiversity conservation, and fisheries management. A lot of expressions that refer to spatial closures in oceans exist such as marine parks, marine sanctuaries, marine reserves, fishery closures, no-take zones, closed areas, and so one. Silva et al. (1986) listed 91 possible denominations. Each term used depends on objectives pursued that are even multiple and divergent. For example, the two terms reserves and closures are specifically used in the context of the fisheries management. Marine reserves are defined as areas where all extractive or harmful human activities (for example, fishing, mining, and drilling for oil) are prohibited whereas fishery closures are areas where fishing for one or more species is forbidden (Grafton et al., 2005). We keep and use interchangeably marine protected areas (MPAs), marine reserves (MRs), and closure terms for describing areas that are permanently closed to some or all of human activity. The objective of this chapter is to present an overview about the economics of MPAs, its importance and how it has been described, analyzed, and modeled through the existing literature (Conrad and D., 2012). Making a review on MPAs analysis consists in a preliminary stage before implementing a bioeconomic model including MPAs. In this current chapter, some questions around the efficiency of MPAs will be first discussed, and then, a review of the bioeconomic modeling process of MPAs in recent literature will be developed, and finally, the challenge through the network dimension of the implementation of MPAs will be outlined in conclusion.

2.2 How to evaluate the efficiency of MPAs?

Marine protected areas are considered as a regulatory tool used for the conservation of natural or cultural resources of the ocean (Sumaila and Charles, 2002) and/or for the improvement of the long term productivity of fisheries. As a management tool for conservation, MPAs also serve as refuge for recovering populations of exploited species and could regenerate habitat modified by fishing activities (Gell and Roberts, 2003). MPAs could also be beneficial to adjacent fisheries by production of spillovers, i.e., net emigration of adults and juveniles across borders and by export of pelagic eggs and larvae. Some authors talked about *double payoff* of marine reserves by increasing both the aggregate biomass inside the reserve and the aggregate harvest in the remaining fishing area (Sanchirico, 2000). Some others talked about the ecological-economic win-win situation with MPAs implementation for both fishes species and fishermen (e.g., (Roberts et al., 2001; Hart, 2006; Dalton, 2010)). Since MPAs are viewed as an important tool for any marine management plan, their effectiveness is also questioned. It might be measured in terms of practical, socio-economic, scientific, and legal performance. The effectiveness of MPAs is questioned because they are not always sufficient by themselves, for instance, in the conservation context (Allison et al., 1998). Used as a complementary tool, MPAs are designed to fight against management failures, for example, in fishing areas (Lauck et al., 1998). According to Hoagland et al. (2001), implementation of MPAs might respond to the main sustainability objectives: biological or ecological, economic, and distributive or social objectives. In other words, MPAs benefits could be quantified in these terms. These points are tackled below.

2.2.1 Ecological benefits

MPAs can ensure the health of the ecosystem within the protected areas including increases in stock abundance, age/size composition, spawning stock biomass (Polacheck, 1990), yield per recruit, restoration of trophic levels, enhance areas of undisturbed habitat (Rodwell et al., 2003) and conservation of marine biodiversity. An important goal, by implementing MPAs, is to reduce or eliminate fishing mortality. Biological efficiency of MPAs is then enhanced by the exchange existing between both protected and non protected areas. The stock effect refers to a dynamic concept by which fish stocks remains inside MPAs to grow and to reproduce (Hoagland et al., 2001). This effect leads to two mechanisms according to Murawski et al. (2005): larval export and biomass export or spillover. The first mechanism explains the export of reproductive outputs (eggs, larvae, pre-recruits) which can increase recruitment in the open areas. The second one is described by the movement of recruited individuals from the closed to open areas. A great biological benefit of marine reserves is also explained by relationships existing between marine reserves and outside areas. Connection of these areas through these relationships is greatly made by the dispersal process. This link can vary depending on the ecological structure, the oceanographic patterns, the level of migrations of fish stocks, and the scale (size) and location of the protected area.

2.2.2 Economic benefits

If biological components could be sufficient to evaluate the efficiency of MPAs in terms of conservation objectives, they could not be enough in the fisheries management context. The economic components must be considered for MPAs and for all other kinds of management tools that point fisheries (Clark, 2006). Few authors are interested in MPAs contribution of achieving economic management goals (Farrow, 1996; Sumaila, 1998, 2002; Alban et al., 2008). MPAs can highly contribute to achieve the socio-economic objectives including protection of essential life stages of commercial species, increase coastal communities revenue from non consumptive uses (diving, photography...), provide adequate areas for scientific research, enhance public education..., .

In economic terms, MPAs could be considered as an investment in which return could be expected. However, as all investments, they are costly and risky to implement (Lauck et al., 1998). In quantitative terms, Balmford et al. (2004) made an evaluation of worldwide cost of MPAs. They found that marine conservation is expensive and the level of the value added is low. On the other side, by improving coastal revenue and increasing biomass, side effects on fisheries as congestion are directly felt in the long run. The recorded social costs on fishing activity are then computed in terms of welfare loss for fishers (Hicks et al., 2004). These effects could be also explained by the increasing competition for the catch of one species by protecting another one under pressure, increasing fuel usage, crew employment, and higher capital costs as well as conflicts between gears. However, Bohnsack (1993) portends that potential conflicts existing before MPAs implementation between commercial and recreational fishers could be reduced with MPAs enforcement.

2.3 Bioeconomic modeling of MPAs

The economic litterature on MPAs is relatively recent (began at the end of the 90's), and a small amount of papers developed this aspect considering MPAs (Alban et al., 2008; Carter, 2003; Farrow, 1996; Milon, 2000; Sumaila, 2002, 1998). Bioeconomic modeling that includes both biological and economic components remains an important analytical tool for the purpose of MPAs in the fisheries management context because MPAs is applied to a multi-disciplinary field: the fisheries management. The special features of the bioeconomic models is that they include both an economic and a biological components Clark (1985). For the most part of MPAs models reviewed here, these components are presented separately.

2.3.1 Biological components

Biological models used for the bioeconomic analysis of MPAs are generally identified as either global surplus models or cohort models.

Global surplus or general biomass or single cohort models provide information about the exploitation of stocks, catches, catchability, fishing effort etc. These models can differ according to the temporal scale. For example, White et al. (2008) used the recruitment model of Ricker [1] defined in discrete time and Hannesson (1998) approximated a Schaefer[2] surplus production model in continuous time.

Multi-cohort models present some features of populations at different stage of life. These models can structure populations by age or length or define a stock recruitment relationship. The Beverton and Holt (1957) stock-recruitment function is considered in Holland (2000), for instance.

These two groups of models (global surplus and cohort models) are characterized by a wide variety of considerations or assumptions made on certain biological parameters including: the larval and adult dispersion, the mobility of adults and juveniles, number of species, fishing mortality, recruitment function, and so one.

Larval dispersion is usually considered as uniform within the protected areas (e.g.,Pezzey et al. (2000)). However the adults dispersion can be assumed four different ways: instantaneous, random (e.g.,Smith et al. (2009)), density-dependence (e.g.,Holland and Brazee (1996)) and dispersion between sink and source[3] (e.g.,Hannesson (1998, 2002)). It is more realistic for some authors to model MPAs by using sedentary or lowly migratory species (e.g.,White et al. (2008)) instead of studying mobile species (e.g., Apostolaki et al. (2002)).

The number of species considered as well as assumptions made on fishing mortality distinguish bioeconomic models of MPAs. Some authors develop a trophic-based modeling or an ecosystem-based modeling (e.g., Beattie et al. (2002)) and other ones simply consider an individual-based modeling (e.g., Anderson (2002); Sumaila (1998)). Two types of assumptions are kept about fishing mortality: (1) either it is considered as constant before and after the reserve creation or (2) it is simply

[1] See Ricker (1954)

[2] See Schaefer (1954)

[3] By source-sink, we mean that some areas have net outflow of dispersal and others have net inflow regardless the levels of the populations (Conrad and D., 2012, p. 76)

transferred from the closed area to the open area after the reserve implementation (Holland and Brazee, 1996).

The dispersal between reserves and outside is also an important point considered in the biological component of MPAs models. This consideration of dispersal in marine reserve models is recent in the bioeconomic context and it was first discussed by Skonhoft and Armstrong (2005). Based on the habitat conditions, literature on marine reserves even assumed that densities of fish are equal for different habitats conditions, that is the assumption of the symmetric density dependence (Armstrong and Skonhoft, 2006). When the asymmetric dispersal process is modeled, the management of outside reserve is shown impacted.

2.3.2 Economic components

Economic models used to analyze MPAs vary from simple revenue-cost economic models, (e.g., Sumaila (2002); Hannesson (2002)) to complex models integrating spatial effort allocation by taking into account the fishers' behavior (Sanchirico and Wilen, 1999; Sanchirico, 2000; Sanchirico et al., 2006; Sanchirico and Smith, 2008). Economic parameters and functions usually used in bioeconomic models of MPAs are the price of fish, the cost of fishing effort, the discount rate, ect. They can serve to determine the long-term profit (Sanchirico et al., 2006) or the discounted economic rent (Sumaila, 1998; Conrad, 1999).

The ex-vessel price of harvest and the unit cost of effort are usually assumed constant in the bioeconomic models of MPAs (Alban et al., 2008). By assuming the constancy of the harvest price, they consider that the market is flexible and competitive, i.e., fishers or agents are so numerous that their actions do not affect the market (they are price taker). In that case, there exist a perfect elasticity between both the demand for harvested fish and the supply of fish measured in terms of fishing effort. In others words, the fishing effort variations of one isolated agent could not affect the fish price.

A key feature: the opportunity cost

The concept of opportunity cost was first developed by John Stuart Mill (1806-1873). It is defined by *the next best alternative that someone has among a lot of available choices that are mutually exclusive.* It comprises monetary or financial costs, lost time, swag, pleasure or any other benefits that provide utility.

The time period considered in marine reserves implementation is always open to debate. Those who advocate in favor of MPAs think it is beneficial in the long run by helping recover fish populations within protected areas and product spillover for outside the reserve. Others, by taking account into potential short run costs, think that marine reserves make fishing activities less valuable, more costly, and then lead to the loss of fishing opportunities.

According to Smith et al. (2010), the economics of marine reserves is politically discussed with special consideration of the opportunity cost. The financial cost as well as the opportunity cost has been also considered. They present a model that predict fishermen's opportunity cost for different time scales. Results obtained from this model vary from short to long runs. The period that comes immediately after the reserves creation, during which fishermen are able to react to the new situations and recovery times of fish populations is relatively short (5 years or more), are considered as short run. In this period, high-skill fishermen are willing to pay (WTP) much more than low-skill fishermen for reserves implementation if stocks are over exploited because reserve creates a lucrative profit opportunity for the former. However, there is any behavioral difference into these two types of fishermen when biomass is higher inside than outside the reserve before its implementation.

The long run period is characterized by the repetition of choices made by the fishermen about the areas to fish because profitability varies over space and time with the adjustment of fish population levels. In this period, the manner of which the opportunity costs of fishermen over time affect the reserves is examined through three biological dispersal scenarios: fishing areas are independent and self-recruiting closed systems (i.e., no dispersal of fish), the reserve is the source (breeding ground) in a source-sink system, and the dispersal process is density-dependent.

1. In a closed system, the opposition to a reserve rises over time and the fishing effort is partially distributed to the remaining fishing areas. A level of the fishing effort is transfered from the reserve to the remaining fishing areas, stocks in these areas decrease while the opportunity cost of reserve increases.

2. In the source-sink dispersal system, opposition to the reserve rises initially and tends to decrease in the long run. Spillovers from the reserve renew the fish

population in the fishing areas. The opportunity cost of the reserve decreases over time.

3. The relative density dispersal system gives an intermediate result. The spillover benefits as well as the opportunity cost of implementing reserve remains low.

The time period affects the economic results with the reserve implementation. However, when fishermen have incomes from non fishery activities a better acceptance of reserve is found in long term or even in short term. When incomes for non fishery activities are significant, the reluctance to the reserve acceptability is lower both in the closed and source-sink system. Finally, the long run extends the gap between low and high-skill fishermen traduced by their willing to pay to implement reserve.

A key feature: the discount rate

Financially, the discount rate is applied for discounting a future payment. It also explains the level of sacrifice that the current generation is capable of doing for the future one. In most of marine reserve bioeconomic models, the economic function is even discounted except for models where biological and/or economic results are expressed in term of sustainability. According to Smith and Wilen (2003), the discount rate represents a necessary condition to generate net economic benefits in reserve implementation. In their dynamic sink source model, Kompas et al. (2004) showed that an increase in the discount rate reduces the optimal reserve size. According to them: *"at a discount rate of more than 20 percent it is economically optimal to establish a marine reserve."*

A stochastic optimal control model in which the intertemporal rent from harvesting only depends on populations of fish located outside of the reserve is used in Grafton et al. (2009). In this model, the discounted rent function to maximize includes an inverse demand function and an aggregate function that both depend on the harvest level.

2.3.3 The spatial representation

The real gap existing between different economic models tackling MPAs is the consideration or not of the spatial dimension. Simple economic models of MPAs are non spatial. Complex models include a spatial dimension and cells considered for spatialization may be assumed homogeneous or heterogeneous.

The spatial heterogeneity is encountered in the most elaborate and recent economic models of MPAs. These works as Sanchirico and Wilen (1999); Sanchirico et al. (2006); Sanchirico (2005) modeled a discrete number of subpopulations in separate zones called metapopulations interconnected by biological relationships including: different life phases, larval, and juvenile or adult movements. Sanchirico et al. (2006) presented a two patches ecological economic model for determining optimal long-term profit. In this model, fish density outside the reserve is assumed spatially uniform and patch to close must have a low biological productivity, a high harvest cost and a net exportation of biomass. They found that optimal reserve-based management is necessary if habitat quality is homogeneous and interpatch larval dispersal is symmetrical.

A key feature: the spatial distribution of the fishing effort

In the spatial management of fisheries there are two components that need to be know: the spatial abundance of marine resources and the spatial behavior of fishermen, i.e., the spatial distribution of fishing effort. With the implementation of MPAs, fishing effort or just a part of it could be moved out to open areas for redistributing or completely disappear. Trying to model characteristics of fleet distribution is a comprehensive method to explain a movement of effort.

The fishing effort redistribution after the reserve establishment and the fishing selectivity must be considered in the evaluation of the marine reserves effectiveness (Apostolaki et al., 2002). Redistribution of fishing effort could be uniformly modeled over the open areas (e.g., Smith and Wilen (2003)) or considered proportional to catch rates or to effort already existing in these areas (e.g., Hannesson (1998)). Including the fishing effort movement in MPAs modeling also emphasize the pre-reserve conditions for which results could widely vary.

2.4 Conclusion

Most of studies considered in this chapter showed the numerous benefits of MPAs and conclude on their effectiveness for conservation as well as for fisheries management. However, the debate remains opened for some aspects about implementation of MPAs such as: management and control costs, real social and economic benefits, the time period, the size and space to be implemented. The latter constitutes a great challenge. Considering the high level of exploitation of fish stocks, damages already caused to the marine ecosystem, and failed management in the past, some authors, organizations, and institutions advocated for a global network of marine reserves that target full variety of life in the sea (plants and animals) (Boersma and Parrish, 1999; Roberts et al., 2001, 2006; Gaines et al., 2010; Costello et al., 2010). Besides biological and management needs, the economic benefits of the implementation of large MPAs are tremendous. According to Costello et al. (2010), significant MPAs could give the maximum fishing profits. However Gaines et al. (2010) think that MPAs do not need to be extensive but smaller strategic MPAs linked in a network could lead to enhance conservation and reduce fishery costs or increase fishery yields and profits for fishermen.

Concretely, the MPAs size in the network context have been suggested. The world parks congress in 2003 suggests that at least 20-30 percent of all marine habitats should be included in networks of marine reserves (Roberts et al., 2005).

According to Gell and Roberts (2003), between 20 and 50 percent of the sea should be protected to achieve the conservation of viable populations, support fisheries management, secure ecosystem processes, and assure sufficient connectivity between marine reserves networks.

The environmental non-governmental organization Greenpeace adopted the goal to protect 40 percent of the oceans and proposed a representative network of marine reserves including large scale reserves beyond national jurisdictions and a lot of smaller marine reserve in coastal areas. For high seas, global network of marine reserves requires a minimum size 5x5 (degrees) at least 560x560 km or 341,000 km^2 at equator (see Roberts et al. (2006) for details). The selection criteria for areas to protect cover the full spectrum of biodiversity and the variation of habitats across the globe (spawning, nursery, breeding, over-wintering habitats must be selected).

As ordinary MPAs, the network MPAs face serious challenges such as: cost of creation (Balmford et al., 2004), their political and social acceptability, the global governance problems (Sanchirico and Wilen, 2007), etc. That could explain why *it has taken 30 years for protecting 1 percent of the ocean in which only 0.1 percent of ocean is fully protected.* The high seas resources and the global governance are the main points that will be developed in the next chapter.

Chapter 3

Specificities of marine protected areas in high seas

Contents

3.1 Introduction

High seas are defined in Article 86 of the United Nations Third Conference on the Law of the Sea in 1982 as areas of the sea not included in the exclusive economic zone (EEZ), the territorial sea, or in the internal or archipelagic waters of an individual country (Nations, 1982). In other terms, all areas of the ocean that lies beyond the 200-nautical-mile limit of the EEZs of coastal states belong to high seas, including open oceans and deep sea environments.

The U.N. Convention on the Law of the Sea (UNCLOS) in its Article 56 provides to the coastal states the full property rights to exploit the fishery resources within their EEZ. The UNCLOS also grants all states to fish freely in high seas and admonishes coastal states and other relevant states to cooperate in order to conserve straddling stocks and highly migratory species found inside and outside high seas (Articles 63 and 64). Contradictions between rights and duties as described in this convention are important and make their management more complex. Straddling stocks designate all stocks found in both EEZ and adjacent high seas excepted highly migratory, anadromous, and catadromous stocks. Although this convention requires the division of duties, rights, and responsibilities between coastal states and distant water fishing nations operating in the adjacent high seas for the conservation and the management of fishing resources, highly migratory and straddling stocks complicate the management of fisheries and create conflicts in high seas (Kaitala and Munro, 1993; Munro et al., 2004). The figure 3.1 provides a spatial representation of shared fish stocks. This figure shows although each country could manage its EEZ areas but they can not control the highly migratory stocks that involve mainly in the high seas environment. In the present chapter, the management tentative of high seas stocks through some regional organizations will be first presented. Economic models that treat the case of high seas resources as well as the management of MPAs in high seas will be also examined.

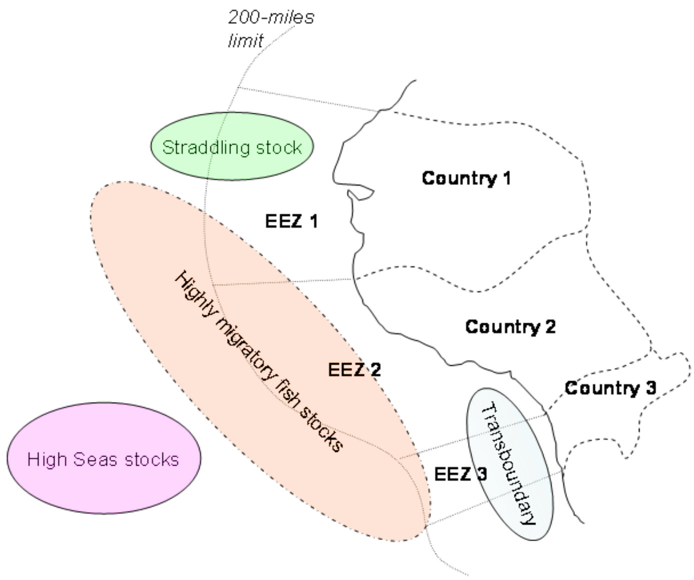


Figure 3.1: Transboundary, Migratory, Straddling and High-Seas stocks [Own elaboration from Munro et al. (2004)]

3.2 Fisheries management in high seas: the real challenge

The difference between the management of a national and an international fishery is that the latter presents more prickly and more pressing distributional problems adding to the highly complex task of managing fishery.

The management of shared resources[1] could result to cooperative decisions of nations either directly or through the regional fisheries management organizations (RFMOs). The natural members of a regional fishery organization are nations that usually manage and exploit the fishery inside the region (Bjorndal et al., 2000).

The establishment of the regional management regime to high seas seems benefit to the member states and obviously attracts new entrants to fisheries. Usual management tools as Total Allowable Catch (TAC), for example, applied to member states, excludes the newcomer's situation in fisheries. From an economic point of view, the non-compliance of these new entrants to the regime status leads to a severe resource depletion (Kaitala and Munro, 1997).

The arrangement based-governance system enforced by RFMOs does not guarantee the achievement of the global management goals (for example, prevent overfishing) because member nations get divergent interests. Crothers and Nelson (2006) presented the management limits of shared stocks fisheries beyond the states jurisdictions carries out through the RFMOs. They remarked that the free riding and the non-cooperation of states are easier and can seem better than the adherence to the RFMOs. This current legal framework and the geopolitical challenges in international waters remain critical. An unified management government or authority in areas beyond states jurisdiction is today promoted because real difficulties to manage shared resources in these areas is that entities or states want each others to fulfill their own goals. The economic analysis of high seas fisheries management could be a good way to quantify gain and loss of welfare of countries or individuals sharing fish stocks. It could also explain why fisheries management in high seas generally failed.

3.3 Economic models of shared fishing resources in high seas

The economic issue can be analyzed the management of shared fishing resources which takes into account stakeholders' behavior can be done through economic

[1] straddling stocks, highly migratory species, and transboundary fishery resources shared by two or more coastal states

models (e.g., Bjorndal et al. (2004)). These models contain both the standard bioeconomic analysis and the game theory. Following the seminal paper by Munro (1979) and the subsequent literature on this issue, shared fish stocks are one of several forms of property rights which can be existed in fisheries (as seen in the 1). Reminding that in the in the common access case, fisheries are exploited without any regulation and fishermen or states can enter until the fishery rent is fully dissipated. This so called bionomic equilibrium is characterized by an overexploitation of the fishery resources from the society's point of view (Gordon, 1954). The "shared fisheries" case is described as an open access fishery in which entry is restricted to a number fixed of countries belonging to RFMOs (Bjorndal et al., 2000). Most of authors who economically analyze the shared stocks issue integrate the strategic interactions as so-called the game theory in their study. The first model that links standard economic model to game theory has been developed by Nash (1953). One of the pioneers who applied the game theory to the fishery resources was Levhari and Mirman (1980). The application of this method to the case of shared fisheries is well used and improved by Munro (1987); Kaitala (1986), ect. Results and conclusion on this issue widely vary from cooperative to non-cooperation situations.

3.3.1 Non-cooperative management

All of studies that face the shared resource management in non cooperative or competitive game lead to the same conclusion: the prisoner's dilemma (Naito and Polasky, 1997; Sumaila, 1999; Levhari and Mirman, 1980). Clark (1980) showed that the result of a dynamic Nash competitive game coincides to the bionomic equilibrium result. Rent is dissipated and in other terms fisheries may face the famous prisoner's dilemma. Exploitation of fisheries resources in a non-cooperative situation whatever the chosen scenario lead to undesirable results for fishing nations (Sumaila, 1999). The payoff from fisheries, in this case, is Pareto inefficient. In other words, some countries could increase their payoff without diminishing those of others.

3.3.2 Cooperative management

Cooperative or joint management of shared stocks is even modeled as a differential game (e.g., Kaitala and Pohjola (1988)). To find cooperative alternatives to share benefits from fishery, the Nash bargaining theory is used. A single cooperative Pareto optimal solution represents the fair and efficient outcome of the negotiation process. However, in cooperative games results widely differ depending on the presence or not the side payments, i.e., transfer payments between players. Compromising harvest policies that integrates the side payments is much more efficient and much less cumbersome than those without side payments (Munro, 1987).

Cooperative management can be disguised by excluding some members or creating restrictions. Lindroos (2004) used a coalitional approach to describe situations of countries that benefit to the fishery without being a member state of the Regional Fisheries Management Organizations. He showed that countries inside the RFMOs (coalition) play a non cooperative game against those outside the coalition. An the other side, if one nation accepts to cooperate, it can choose to adopt agreements immediately or a long time after. Kaitala and Lindroos (2004) determined many factors that influence time to adopt an agreement. They showed that delay to ratify a multilateral agreement by countries depends to their fishing capacity, their unit cost of harvesting, the initial stock level of biomass, the carrying capacity, the growth rate of the stock, the price of harvesting, and the discount rate. This last parameter can make cooperation agreements impossible if countries are reluctant and impatient to get higher benefits from fishery (Vallée et al., 2009). Hence, we can understand why the UNCLOS was entered into force until 16 November 1994 in spite of it was started to signature since 10 December 1982.

3.4 Economic model of MPAs locating in high seas

Literature on MPAs in areas beyond national jurisdiction is under-developed. There exist an increasing amount of technical papers that deal with High Seas MPAs (HSPMAs) in their general sense (Corrigan and Kershaw, 2008; Gjerde and Kelleher, 2005). Scientific works on this issue are as sparse as recent (e.g., Ruijs and Janmaat (2007); Ardron et al. (2008); Hislop (2007); Game et al. (2009); Kaplan et al. (2009)) ect. They all concern the management problems in MPAs beyond EEZs. Ruijs and Janmaat (2007) presented implementation of MPAs placed in transboundary areas. Their model considers results of MPAs that vary following cooperative and competitive situations. Ardron et al. (2008) presented the Marine Spatial Planning (MSP) as a way to enhance HSMPAs management. If usual monitoring methods used to analyze HSMPAs are even incorrect and a lack of data, the MSP will seem to be the adequate tool to correct these failures. Hislop (2007) specifically approached the governance problem and suggested a management method based on a multi-agreement system between a small number of countries differenced by their technological capacity and their political will. The last two articles address the governance issue through other major challenges of pelagic species. Biological, physical, design and governance challenges are advanced and solutions are also proposed by Game et al. (2009). In response to this paper, Kaplan et al. (2009) based on such realistic examples to analyze more deeply some of these challenges, and they contest some of these solutions suggested by the former. Despite that a lot of challenges are addressed, the economic issue for high seas MPAs remains a key question to address. Sumaila et al. (2007) is one of the few studies that economically tries to quantify potential benefits and costs of MPAs locating outside national jurisdiction. Based on the current legal framework and the marine resources exploitation trends, they are critical on success of cooperative management in high seas where countries may face different level of costs and benefits.

3.5 Conclusion

The problem of the High Seas governance has been briefly surveyed in this chapter, although a deeper analysis of this literature would go beyond the scope of this thesis (see for an extensive discussion about governance problems in the high seas the comprehensive survey by Munro et al. (2004)). The UNCLOS through diverse articles present measures to protect and preserve the marine environment by limiting conflicts between stakeholders. These measures apply to all marine spaces, including high seas and deep sea bed, aim mainly to protect rare or fragile ecosystems and species endangered (see article 194).

MPAs is hence one of the most effective instruments to implement these measures and also they are a real example of Area Based Management Tools (ABMTs). Current legal framework considers ABMTs as an important method to address international governance gaps on the high seas. The UN Secretary-General report on "oceans and the law of the sea" promoted and encouraged to adopt ABMTs as a precautionary approach in areas beyond national jurisdiction. Indeed, the decision making of both implementation and management of MPAs to high seas is relevant to the regional fisheries management organizations. That means that all fisheries management tools used in high seas including MPAs depend first on cooperative agreements. However, MPAs may constitute an efficient tool to repair damage caused by the non cooperative fisheries that evolve in high seas.

Part III

The global tuna commodity chain

Chapter 4

The network structure of the global tuna commodity chain

Contents

4.1 Introduction

We are interested in the tuna commodity chain defined as all operations realized from the exploitation of the tuna stocks until the final sale or consumption of tuna commodities. Our goal is to provide a global view about this commodity chain. This objective is naturally related to considerations about climate change and the economic globalization context. Building the network structure is a first step towards the analysis of how some environmental and economic changes may affect the tuna commodity chain.

In a network building of the global tuna commodity chain, we have to define nodes and links. Nodes will be: biological stocks (fish populations), fleets, fresh or frozen fish markets, transformation industries (canning) and transformed fish markets.

First, we explain how this work is based on existing statistics concerning stocks (defined by areas, catches, and species), fleets (defined by areas, catches, and countries), markets (commodities, countries, and exchange flows). Then, we propose a method to homogenize these statistics in a common framework, unifying nomenclatures and solving both incoherences and heterogeneity in data. Finally, we give some presentations of the database. The reader can find detailed informations in a supplementary material file.

4.2 Data collection and structure

This work is data intensive. Sardara, Fishstat, Eurostat, Organization for Economic Co-operation and Development (OECD), and some national statistics provided all necessary data. These sources of data provide information to implement the network structure for the worldwide tuna commodity chain. The Sardara database gives information related to exploitation of the worldwide tuna stock (catches, fishing effort,...) while the three other databases provide information about the worldwide tuna markets (commodities, exchange flows...). Structure and specific informations from each database will be detailed in the following section.

4.2.1 The SARDARA database

The SARDARA database contains data that have been collected and pre-processed by the Regional Fisheries Management Organization (RFMO). Its purpose is to give to fisheries scientists a global view on the tuna exploitation. The basic unit of information is the catch in volume and the level of fishing effort by unit of effort. This database corresponds to the period from 1950 to 2005 for the three oceans: Indian, Atlantic, and Pacific. For the Atlantic and Indian oceans some data are available until 2007. Two types of data with different structure are used to build SARDARA: nominal catches (NC) files and catches/effort (CE) files. The NC files give nominal catch by country, by year, and by gear with no spatial reference and the CE files give catches and the fishing effort data by country and by month with their spatial coordinates. The spatial grid is defined by 5 x 5 degrees for data from longline (most of them), small scale fisheries, and all fisheries that are involved in the Pacific ocean. This spatial scale for fisheries data from the Pacific ocean is due to either the non availability or the bad quality of these data. However, the 1 x 1 degree grid is used for surface fisheries like purse seine. For this work, all data about the worldwide tuna (all species) fisheries come from SARDARA database. The final structure of this database represents catches and fishing effort data given by ocean, spatial unit, year, country, gear, and unit of the fishing effort. The last one gives the expression of the fishing effort by the corresponding gear. For example, the corresponding effort to purse seine fishery is the number of days at sea.

SARDARA has been chosen mainly to solve a problem with the spatial resolution. Other databases like Fishstat (capture and production dataset) from FAO (Food and Agriculture Organization) provides catches data by FAO areas[1]. As we intend, in a forthcoming work to focus on the Indian ocean, the scale was too large as well as inappropriate for this work. Databases from the three tuna commissions: Indian Ocean Tuna Commission (IOTC), Inter-American Tropical Tuna Commission (IATTC), International Commission for the Conservation of Atlantic Tunas(ICCAT), and Western and Central Pacific Fisheries Commission (WCPFC) are specific by ocean, data are available for some species (the most fished by ocean), not always spatial, and normally their structure is different by commission therefore more difficult to treat.

As usual, we must face the problem of normalizing the fishing effort. In SARDARA, the corresponding effort to a given catch may be: the number of days at sea, fishing days, hooks, boats, trips, traps per day or the number of lines per day. To get an homogenized value of the fishing effort, we have proceeded in a quite rough manner as follows:

1. We have built the following prices for species (cf. Table A.3).

2. We have supposed that, on a long term period, different effort will correspond to the same income. In other words, we standardized the fishing effort in order that, for different fishing effort type, each fishing effort unit provides

[1] FAO areas are described by 19 major fishing areas. See *http://www.fao.org/fishery/area/search/en* for details

ALB	Thunnus alalunga	1.8
BET	Thunnus obesus	4.9
BFT	Thunnus thynnus	9
SKJ	Katsuwonus pelamis	2
YFT	Thunnus albacares	2

Table 4.1: Tuna species price in US dollar per Kg

the same level of income. We found the following coefficients for all types of effort (cf Table 4.2).

Gear	Effort unit	normalized effort value
Purse seine	Number of days at sea	7
Bait boat	Number of fishing days	250
Longline	Number of hooks	0.01
Gillnet and AFIO	Number of boats	0.8
Gillnet and AFIO	Number of trips	0.3
Fishing trap	Number of traps per day	300
Pole and line	Number of lines per day	1.2

Table 4.2: Value of the normalized fishing effort per gear
AFIO means non specified small scale fisheries in Indian ocean

3. Finally, we obtain a database of catch from SARDARA, where:

- The period is 1993-2006 (14 years)
- The fishing areas are defined by 10 by 10 degrees in the Indian ocean and 30 by 30 degrees elsewhere, and they are selected in order to provide more than 90% of the values of global catches, all species together.
- Fleets correspond to national pavilions representing 90% of the values of global catches, all species together.

All entities selected are as follows:

- Areas: they are represented in the figure 4.1
- Species: ALB, BET, BFT, SKJ, YFT
- Fleets: COL, ECU, ESP, FRA, IDN, ITA, JPN, KOR, MAR, MEX, PHL, SYC, THA, TWN, USA, VEN

In the figure 4.1 a selected area is represented by 30 x 30 degrees excepted in Indian ocean where a higher resolution is taken (10 x 10 degrees). Areas are selected where a representative fishing activity is existent. This work considers all the three oceans and is not obviously extended to polar zones.

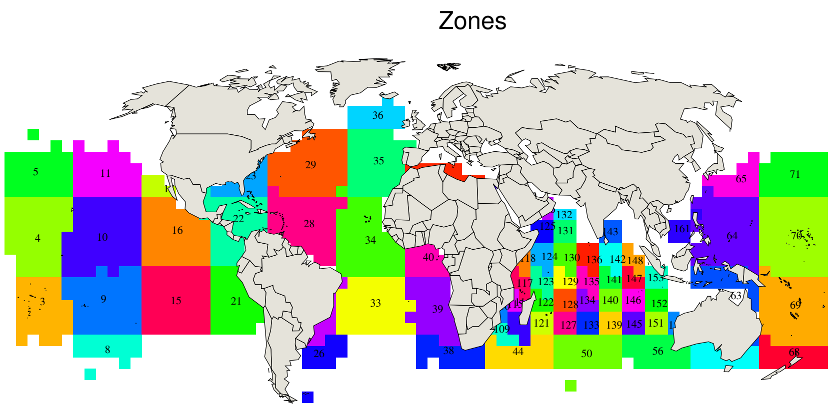


Figure 4.1: Selected areas

4.2.2 The FISHSTAT commodity database

The Fishstat commodities database belongs to the Fishstat database from FAO. Data available in this base come from official reports of countries. For the purpose of this study, all reported countries in all continents are first selected. And then, all tuna commodities based on the United Nations Standard International Trade Classification (SITC) have been chosen. The SITC is a classification system maintained by the United Nations statistic division for grouping goods or commodities entering external trade (exports and imports). This classification allows to compare different countries, years, and commodities. See *http://unstats.un.org/unsd/trade/sitcrev4.htm.*

The Fishstat commodities database is relevant of the General Trade System. This system records total imports and total exports (general imports and exports including re-exports), while the special trade system records only imports for domestic consumption and exports of domestic goods (special imports and exports). General imports consist of all imports which enter into a country, including goods for domestic consumption and imports into bonded warehouses or free zones. General exports consist of the combined total of national exports and re-exports. Re-exports, in the general trade system, consist of the outward movement of nationalized goods plus goods which, after importation, move outward from bonded warehouses or free zones without being transformed. Special exports comprise exports of goods wholly or partially produced or manufactured inside the country, together with exports of "nationalized goods", but not the goods held in bonded warehouses or free zones. We have chosen countries belonging to the general trade system.

Both volume and value data of production, export, and import for tuna commodities are extracted from this database. Data on volume are expressed in tonnes and refer to the net weight of the commodities. Those on the values of tuna commodities imports and exports are expressed in thousands of current US dollars. The selected entities for the tuna commodities are those as follows:

1. Selected years are: 1993-2006

2. Selected categories are:

    (a) Fresh and frozen categories: fresh albacore (ALB-FRE), frozen albacore

(ALB-FRO), fresh bigeye tuna (BET-FRE), frozen bigeye tuna (BET-FRO), fresh skipjack (SKJ- FRE), frozen skipjack (SKJ-FRO), fresh bluefin (BFT-FRO), fresh yellowfin tuna (YFT-FRE), frozen yellowfin tuna (YFT-FRO), fresh tuna (TUN-FRE), and frozen tuna (TUN-FRO)

(b) Prepared [2] categories: prepared albacore (ALB-PRE), prepared skipjack (SKJ-PRE), and prepared tuna (TUN-PRE)

Their correspondence with the FAO nomenclature is given in table 4.3. They are selected in order to represent more than 80% of the total tuna commodi-tities.

3. Selected trading countries are: BRA, CAN, COL, ECU, ESP, FRA, GER, IDN, ITA, JPN, KOR, MEX, NET, PHL, SYC, THA, TWN, UK, USA, VEN They represent 80% of the total of Production + Import + Export.

The eurostat database and other national statistics are used to improve and correct the commodities data extracted from the Fishstat database. These data are related to the value of exchange flows among countries (import and export data), and the national production and consumption of fresh or frozen tuna one side and prepared tuna on the other side.

[2] For the need of this work we use interchangeably prepared and canned commodities that refer to all prepared tuna commodities.

Albacore (=Longfin tuna), fresh or chilled	ALB, FRE
Albacore (=Longfin tuna), frozen, nei	ALB, FRO
Albacore (=Longfin tuna), gilled, gutted, frozen	ALB, FRO
Albacore (=Longfin tuna), heads-off, etc., frozen	ALB, FRO
Albacore (=Longfin tuna), prepared or preserved, not minced, in oil	ALB, PRE
Albacore (=Longfin tuna), prep. or pres., not minced, nei	ALB, PRE
Atlantic(Thunnus thynnus)and Pacific(Thunnus orientalis)bluefin tuna, fresh or chilled	BFT, FRE
Atlantic(Thunnus thynnus)and Pacific(Thunnus orientalis)bluefin tuna, frozen	BFT, FRO
Bigeye tuna, fresh or chilled	BET, FRE
Bigeye tuna, frozen, nei	BET, FRO
Bigeye tuna, gilled, gutted, frozen	BET, FRO
Bigeye tuna, heads-off, etc., frozen	BET, FRO
Bonito, frozen	BON, FRO
Bonito (Sarda spp.), not minced, prepared or preserved, nei	BON, PRE
Euthynnus excl. skipjack or stripe-bellied bonitos, fresh or chilled	SKJ, FRE
Euthynnus exc. skipjack or stripe-bellied bonitos, frozen	SKJ, FRO
Euthynnus other than skipjack prep. or pres. not minced, nei	SKJ, PRE
Loins of Euthynnus other than skipjack, prep. or pres.	SKJ, LOI
Skipjack prepared or preserved, not minced, nei	SKJ, PRE
Skipjack, prepared or preserved, whole or in pieces, not minced, in oil	SKJ, PRE
Skipjack tuna, fresh or chilled	SKJ, FRE
Skipjack tuna, frozen	SKJ, FRO
Skipjack tuna, gilled, gutted, frozen	SKJ, FRO
Skipjack tuna, heads-off, etc., frozen	SKJ, FRO
Southern bluefin tuna(Thunnus maccoyii), fresh or chilled	BFT, FRE
Southern bluefin tuna(Thunnus maccoyii), frozen	BFT, FRO
Tuna loins, prepared or preserved	TUN, LOI
Tunas, bonitos, billfishes, fresh or chilled, nei	TUN, FRE
Tunas, flakes and grated, prepared or preserved	TUN, PRE
Tunas, fresh or chilled, nei	TUN, FRE
Tunas, gilled, gutted, frozen, nei	TUN, FRO
Tunas, heads-off, etc., frozen, nei	TUN, FRO
Tunas nei, frozen	TUN, FRO
Tunas prepared or preserved, not minced, in airtight containers	TUN, PRE
Tunas prepared or preserved, not minced, in oil	TUN, PRE
Tunas prepared or preserved, not minced, nei	TUN, PRE
Tunas prepared or preserved, not minced, not in airtight containers	TUN, PRE
Yellowfin tuna, fresh or chilled	YFT, FRE
Yellowfin tuna, frozen, nei	YFT, FRO
Yellowfin tuna, gilled, gutted, frozen	YFT, FRO
Yellowfin tuna, heads-off, etc., frozen	YFT, FRO

Table 4.3: Tuna commodities

4.3 Matching the catch dataset and the commodity dataset

SARDARA database and the FISHSTAT commodity dataset are the two main databases that provide data for the achievement of this work. However, coherence problems point out between these two bases :

- Some common entities found both in SARDARA and FISHSTAT are defined differently. Species found in SARDARA are not clearly defined as such in FISHSTAT. In the latter, species are represented by the commodity and not by the name of the species. The main reason is that the commodity may be a mix of species (the tuna commodity, for example).
- Commodities data are unavailable in some cases.

Moreover, data on commodities production, import, and export are even available while those of the bilateral exchange flows are rarely found in these two databases. The value of flows between countries are generally found in the national statistics of some countries. However, in a network approach, analyzing the values of flows is a crucial issue.

To solve these problems, we match catch and production of some commodities by country. The following section details the method used to build the network structure of the worldwide tuna commodity chain by taking into account these incoherences.

4.3.1 Coherence constraints

We need a network that is coherent in the sense that at each node there is a balance between input and output, taking into account that some node may process to a transformation of the nature of commodity; for example, transforming fresh or frozen fish to prepared fish. The network structure of the global tuna chain is displayed in figure 4.2. In this figure, green flows are for FF fish and yellow ones for canned commodities.

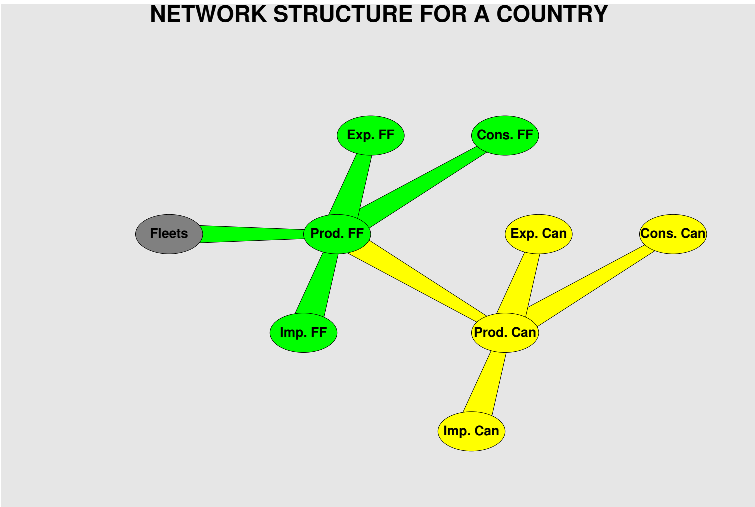


Figure 4.2: The network structure of the global tuna chain

For each country,

- tuna catches directly provide the fresh and frozen production (prod. FF),
- for all fresh and frozen commodities, the total sum of the production plus the import (imp.FF) must be equal to the total sum of the consumption (Cons. FF) plus the export (Exp. FF),
- for all fresh and frozen commodities, the final consumption is provided by the direct consumption plus the canning production,
- and for all canned or prepared commodities, the total sum of the production (Prod.Can) plus the import (Imp.Can) must be equivalent to the total sum of the consumption (Cons.Can) plus the export (Exp. Can).

For all the both commodities

- total imports must be equivalent to total exports

We denote, a the fishing area, e the species, p, q the pavilions, fleets or countries, f the fresh or frozen fish commodities, c the prepared fish commodity. Then, we denote the network flows as follows:

- $X_{ae,ep}$: catches
- $X_{ep,fp}$: from catches to commodities (fresh or frozen)
- $X_{fp,fq}$: import or export of fresh or frozen fish between countries
- X_{fp}: sales of fresh fish on a national market
- $X_{fp,cp}$: national consumption of fresh or frozen fish for preparation
- $X_{cp,cq}$: import or export of prepared fish between countries
- X_c^p: national consumption of prepared fish

For all countries p and for all fresh or frozen fish commodities f the balancing of exchanges are given by:

$$\sum_e X_{ep,fp} + \sum_q X_{fq,fp} = \sum_q X_{fp,fq} + \sum_c \theta_c X_{fp,cp} + X_{fp}$$

In this equation, the total sum of production of fresh and frozen tuna for all species plus the total sum of imports of fresh and frozen tuna of importer country q are equal to the sum of exports of these commodities from country p plus the total consumption of prepared tuna from fresh and frozen fish for all prepared commodities and the total sale of fresh and frozen commodities that are destined to the local consumption.

The coefficient θ_c is the transformation coefficient of fresh and frozen commodities to prepared commodities.

On the other hand, for all countries p and for all prepared commodities c, the exchange flows are quasi similar to fresh and frozen commodities and are given by:

$$\sum_f X_{fp,cp} + \sum_q X_{cq,cp} = \sum_q X_{cp,cq} + X_{cp}$$

As the fresh and frozen commodities exchange flows, the first term of this equation is described by the total production and the total imports of prepared tuna. However, in this case the total production of prepared commodities is only the national consumption of fresh and frozen tuna used for getting the prepared tuna. The balancing is given by the second term that represents the sum of the total exports of prepared tuna and the national consumption or the total sales of prepared tuna.

In order to solve the previous equations, i.e., to find situations that maintain the equilibrium, we formulate definitions about all possible scenarios. They are as follows:

- $\overline{X_{ae,ep}} \simeq X_{ae,ep}$, catches (Sardara)
- $\overline{S_{fp}} \simeq \sum_e X_{ep,fp}$, commodity production, fresh or frozen (Fishstat)
- $\overline{I_{fp}} \simeq \sum_q X_{fq,fp}$, imports of commodity, fresh or frozen (Fishstat)
- $\overline{E_{fp}} \simeq \sum_q X_{fp,fq}$, exports of commodity, fresh or frozen (Fishstat)

Hence, we assume that existing exchange flows among some entities are constrained by some "connectivity tables" expressing that, from our knowledge, a transformation, an exchange is possible or not. To do this, we used other databases such as Eurostat. We formulate the main constraints as follows:

- For all p, $X_{ep,fp} > 0$ only if $K_{ef} = 1$, i. e., when there may exist flows between one species and one fresh or frozen commodity
- For all p, $X_{fp,cp} > 0$ only if $H_{fc} = 1$, i. e., when there may exist flows between one fresh or frozen commodity and one prepared commodity
- For all f, $X_{fp,fq} > 0$ only if $L_{fp,fq} = 1$, i. e., when there may exist flows between two countries for one fresh or frozen commodity
- For all c, $X_{cp,cq} > 0$ only if $L_{cp,cq} = 1$, i. e., when there may exist the flows between two countries for one prepared commodity

Under these hypotheses, we compute the values of flows of an homogenous network, in which:

- $\overline{S_{cp}} \simeq \sum_f \theta_c X_{fp,cp}$: the national production of a prepared commodity

	ALB	BET	BFT	SKJ	YFT
ALB-FRE	1	0	0	0	0
ALB-FRO	1	0	0	0	0
BFT-FRE	0	0	1	0	0
BFT-FRO	0	0	0	0	0
BET-FRE	0	1	0	0	0
BET-FRO	0	0	0	0	0
SKJ-FRE	0	0	0	1	0
SKJ-FRO	0	0	0	1	0
YFT-FRE	0	0	0	0	1
YFT-FRO	0	0	0	0	1
TUN-FRE	1	1	1	1	1
TUN-FRO	1	1	1	1	1

Table 4.4: From tuna species to FF commodities

	ALB PRE	SKJ PRE	TUN PRE
ALB-FRE	1	0	1
ALB-FRO	1	0	1
BFT-FRE	0	0	1
BET-FRE	0	0	1
BET-FRO	0	0	1
SKJ-FRE	0	1	1
SKJ-FRO	0	1	1
BFT-FRO	0	0	1
YFT-FRE	0	0	1
YFT-FRO	0	0	1
TUN-FRE	0	0	1
TUN-FRO	0	0	1

Table 4.5: From FF to prepared commodities

- $\overline{I_{cp}} \simeq \sum_q X_{cq,cp}$: the imports of a prepared commodity (from Fishstat)
- $\overline{E_{cp}} \simeq \sum_q X_{cp,cq}$: the exports of a prepared commodity (from Fishstat)

Now, we can mathematically write the problem. It consists in finding a vector of homogeneous flows $X = (X_{ae,ep}, X_{ep,fp}, X_{fp,fq}, X_{fp,cp}, X_{cp,cq})$, i.e., satisfying a set of constraints K, that minimizes S, the sum of squares of the differences between known and computed flows. We have:

$$\begin{aligned} S &= \sum_{a\to e}(\overline{X_{ae,ep}} - X_{ae,ep})^2 \\ &+ \sum_{fp}(\overline{S_{fp}} - \sum_{e} X_{ep,fp})^2 + \sum_{fp}(\overline{I_{fp}} - \sum_{q} X_{qf,pf})^2 + \sum_{fp}(\overline{E_{fp}} - \sum_{q} X_{cp,cq})^2 \\ &+ \sum_{cp}(\overline{S_{cp}} - \theta_c \sum_{a} X_{fp,cp})^2 + \sum_{cp}(\overline{I_{cp}} - \sum_{q} X_{cq,cp})^2 + \sum_{cp}(\overline{E_{cp}} - \sum_{q} X_{cp,cq})^2 \end{aligned}$$

And the set of constraints K is:

- $X_{ep,fp} > 0$ only if $K_{ef} = 1$, for all p, e, f,

- $X_{fp,cp} > 0$ only if $H_{f_c} = 1$, for all p, f, c ,
- $X_{fp,fq} > 0$ only if and $L_{fp,fq} = 1$, for all f, p, q,
- $X_{cp,cq} > 0$ only if and $L_{cp,cq} = 1$, for all c, p, q,
- $\sum_e X_{ep,fp} + \sum_q X_{fq,fp} = \sum_q X_{fp,fq} + \sum_c \theta_c X_{fp,cp} + X_{fp}$, for all p, f,
- $\sum_f X_{fp,cp} + \sum_q X_{cq,cp} = \sum_q X_{cp,cq} + X_c^p$, for all p, c.

This is a constrained quadratic problem. It is large (more than 1000 variables) but accessible with computation, due to progresses of optimization algorithms.

4.4 Conclusion

This chapter has been essentially dedicated to explain the process of data extraction and analysis. The main sources of data extraction (Sardara and Fishstat) have been highlighted and discussed. The Sardara database provides catch and effort data whereas from Fishstat we extracted production, export, and import data in both volume and value. The methodology used to analyze data is based on their representativeness. Although necessary data have been found, their improvement has been an important issue. By homogenizing disparate data, a coherent system with representative entities (area, species, country, and commodity) has been represented. This preliminary work on data also allowed the network structure of the tuna chain to be built. The description of the tuna supply chain is then made through a network structure using the network dynamics approach. This formulation of the problem resulted to find a coherent network system. The description of these entities that characterize the network system is the aim of the following chapter.

Chapter 5

Main features of the global tuna commodity chain

Contents

5.1 Introduction

In the previous chapter, the methodology used to both explore and analyze data has been succinctly explained. This stage allowed to characterize the network structure of the tuna chain. The characterization of this structure is made through entities that have been already cited in the previous chapter, that are: area, species, country, and tuna commodity. Thus, the tuna commodity chain has been associated to a structure of a dynamic network. This network is identified as diverse, including distribution of areas of main tuna species, fleets, and commodity markets. What we have got is homogeneous in the following sense: for each entity, a node of the network, inflows are related to outflows.

In the present chapter, we identify the main processes of the dynamic network. The characterization of the network structure is an important stage that allows describing all components of the structure: nodes, links, and flows. Both trends and evolution of these components obviously are not without impacts on this dynamic structure. The description of the all entities in the network will be made and will be displayed through several graphs and maps. Emphasis will be put on tuna catches by country as well as on worldwide tuna markets. Great trends as well as significant facts about selected entities will be analyzed. Detailed comments will be made on results. Some previous studies in the literature about tuna stocks status and markets will use for a better discussion.

5.2 Main features of entities

This section provides descriptions of main tuna characteristics. They are presented for entities defined inside the network structure. These entities are given by: tuna catches and stocks, fleets, fresh and frozen tuna commodities, and canned or prepared commodities. They intervene in the tuna chain process and are defined as nodes in the network structure. All these entities are represented by data from Sardara, Fishstat, and the other databases already cited in the previous chapter.

5.2.1 Worldwide distribution tuna catches

The figure 5.1 gives the catches distribution of selected species by area. Skipjack tuna is the most distributed tuna species in the worldwide ocean. Skipjack, bigeye, and yellowfin tuna are tropical species distributed over the three oceans. Bluefin tuna is a temperate species and is harvested essentially in the North Atlantic ocean. Albacore catches are situated in both tropical and temperate waters in the three oceans but a few more in temperate waters.

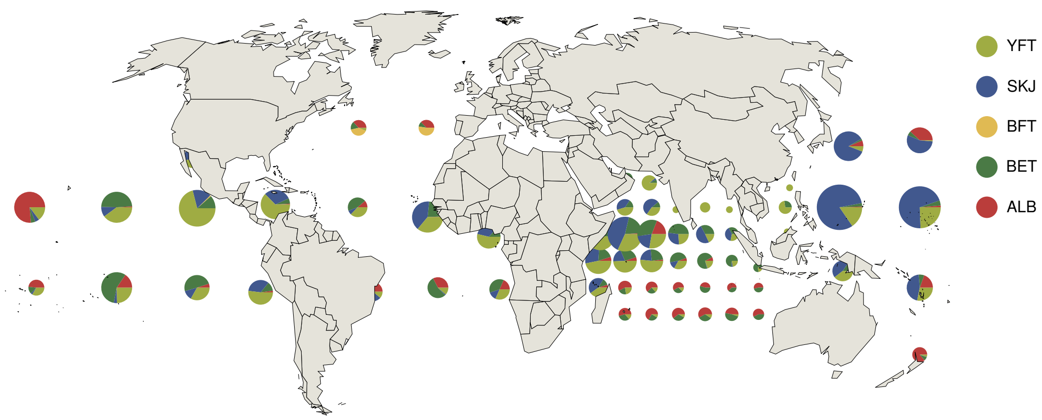


Figure 5.1: Worldwide distribution of tuna catches

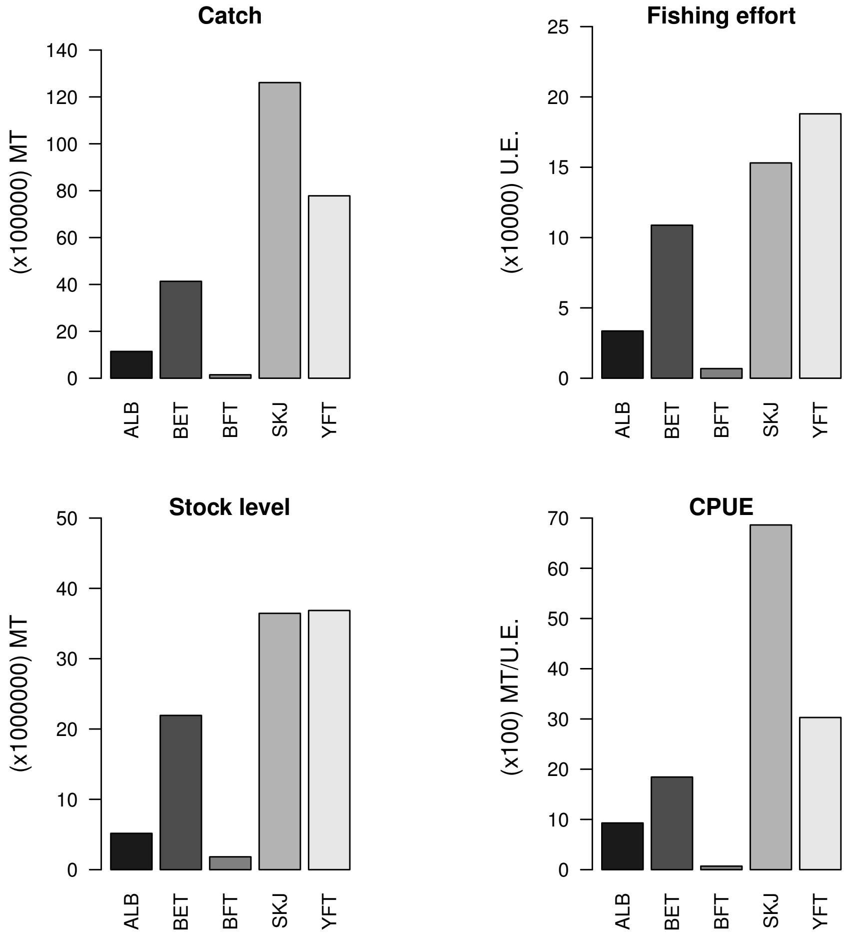


Figure 5.2: Average *stock,* catch, effort, and CPUE (2002-2006)

5.2.2 Catch, *stock*, fishing effort, and CPUE comparison by tuna species

The figure 5.2 (top) displays, for the period 2002-2006, the average total catches and effort by tuna species. The average total stock and CPUE by species (down) presented are both computed (details on computation method for stock will be showed in the chapter model calibration). The skipjack tuna is the most caught species with more than 1 million tons by year on average for the period. However, its total fishing effort is not the highest and reaches 15 thousand of the unit effort. The level of skipjack stocks is estimated to more than 1 million tons on average for the period but not the highest level. This species remains the most abundant according to the level of the CPUE that could reach 7 thousand of tons per the unit of effort. The yellowfin tuna also gives noticeable informations. It is the second most fished tuna species, gets the highest fishing effort, the highest level of tuna stocks, and the second most abundant tuna species. On the side of these species, there is the bleufin tuna that is also noticeable but in the opposite sense. It is the tuna species the least caught in quantity but its stock level and the cpue are the lowest. The bigeye tuna and the albacore are also both tuna species on which we get focus by their catches and fishing effort as well as their stock level. More detailed comments about the healthiness of stocks for each tuna species will be done later.

5.2.3 Main fleets that exploit tuna

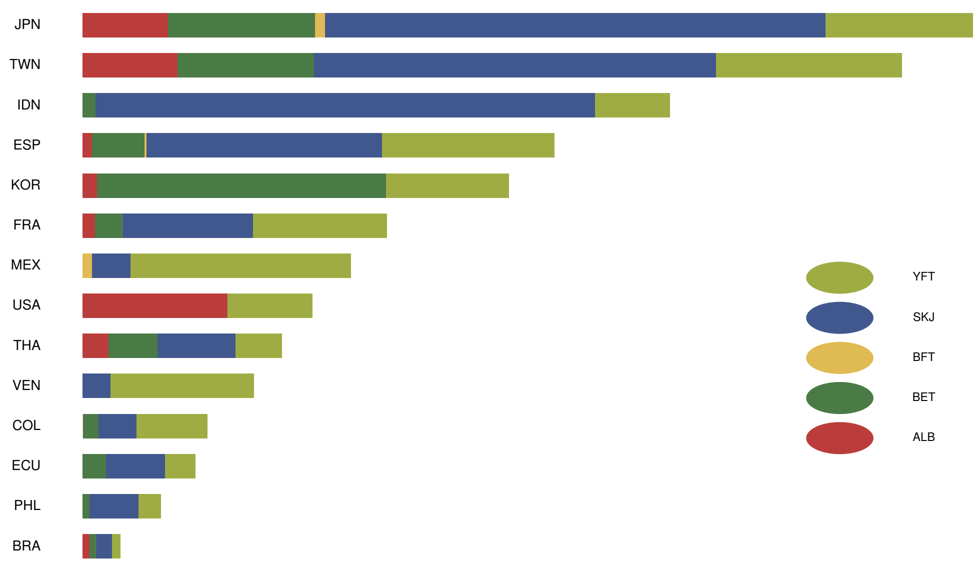


Figure 5.3: Specific composition of tuna catches for the top fleets

Catches by fleets and by species are represented in figure 5.3(See the list of abbreviations available). Dominant fleets are countries that catch the most important part of the all tuna species around the world ocean. Japan is the largest fleet in the world followed by Taiwan. These fleets catch at least three of the five most abundant tuna species. Skipjack, yellowfin, and bigeye tuna are the most caught by all fleets. Albacore is mainly targeted by USA and bluefin by Japan and Spain.

5.2.4 Average catch, fishing effort and CPUE comparison by fleet

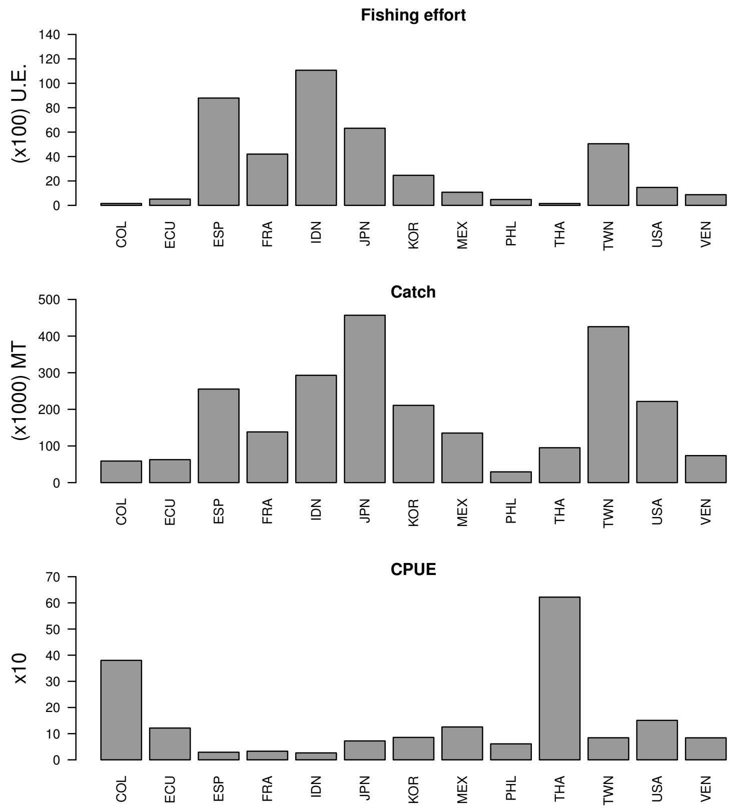


Figure 5.4: Average catch, fishing effort, and CPUE by fleet (1993-2006)

The figure 5.4 displays the total tuna catches, fishing effort, and CPUE on average by year for all tuna species for the period 1993-2006. Japan, the largest fleet of the world, harvests more than 450 thousand metric tons on average by year. The second largest fleet, Taiwan caught some 400 thousand tons. The third fleet in catches, Indonesia which catches reaches an average 300 thousand tons is the first fleet for the fishing effort used that could be some 12000 normalized unit of effort (U.E.). The fishing effort on average by year for the period is also high for Spain (8000 U.E.). It is viewed as normal for the rest of the top fleets compared to the level of catches except Thailand whose fishing effort is very low.

5.2.5 Featuring the specific composition by fleets

The worldwide tuna exploitation is characterized by a wide range of variations during the period 1993 to 2006. The manner to consider these changes could be determined by the catches, the fishing effort, and the catches per unit of effort levels. Here is the specific composition per each selected fleet.

5.2.5.1 Tuna catches

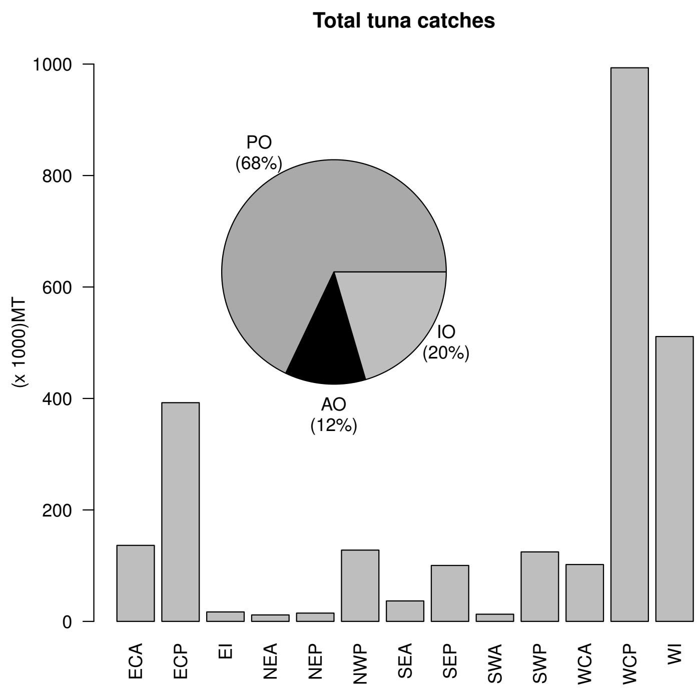


Figure 5.5: Worldwide average catches from 1993 to 2006

The figure 5.5 displays the average total tuna catches from SARDARA data base, for all species, all gears, all countries, and all fishing areas from the period 1993-2006. The fishing areas are here showed by the main FAO areas (e.g. ECA for Eastern Central Atlantic, see the list of abbreviations) The tuna catches are extended over all the three oceans. Only 12% of the total tuna catches come from the Atlantic ocean, and catches are concentrated only in its central part. The Pacific ocean, with 68% of catches, gives the highest level of the total tuna catches and the higher concentration is in its central parts (eastern and western). In the Indian ocean, the concentration of tuna catches is high in the western parts, and total catches in this ocean represent 20% of the worldwide tuna catches.

5.2.5.2 Fishing effort deployed to catches tuna

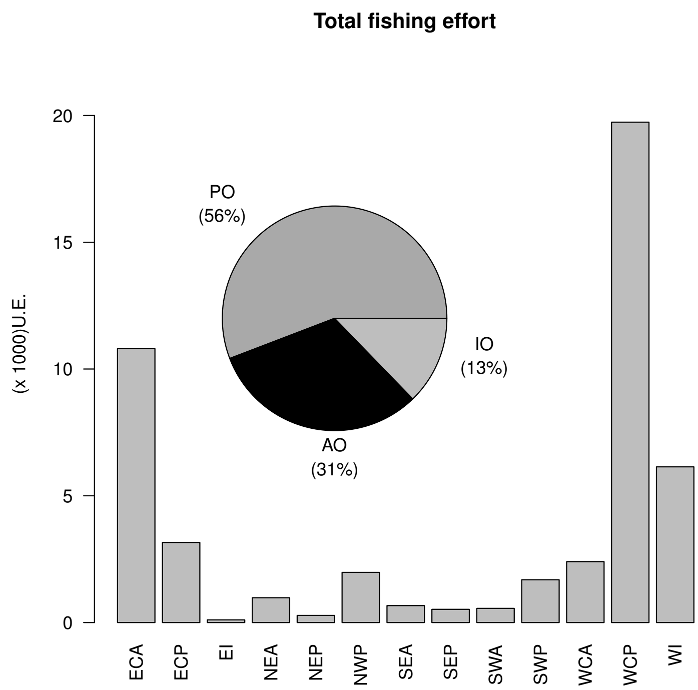


Figure 5.6: Average Fishing effort from 1993 to 2006

The figure 5.6 (down) shows the average total normalized fishing effort from 1993 to 2006 deployed to catch tuna for the three oceans. The Pacific ocean gives the highest level with 56% of the total fishing effort, and the higher concentration in its western central part. The fishing effort level is also high in the Atlantic ocean, compared to the catches level. It represents 31% of the total fishing effort that is mainly spread out in the eastern central region. The Indian ocean, the second ocean in tuna catches, gets only 13% of the total fishing effort. This effort is mainly expended in the western part.

5.2.5.3 The catches per unit of fishing effort (CPUE) index

The catch per unit of effort could be considered as an index of abundance. The figure 5.7 shows that the tuna species is more abundant in the eastern Indian ocean and the southeast Pacific ocean. This high level of the CPUE in these areas could be explained not by the level of catches but by the lowest level of the fishing effort. The fishing pressure that evolves in the Atlantic ocean through the fishing effort could explain the lowest abundance of tuna.

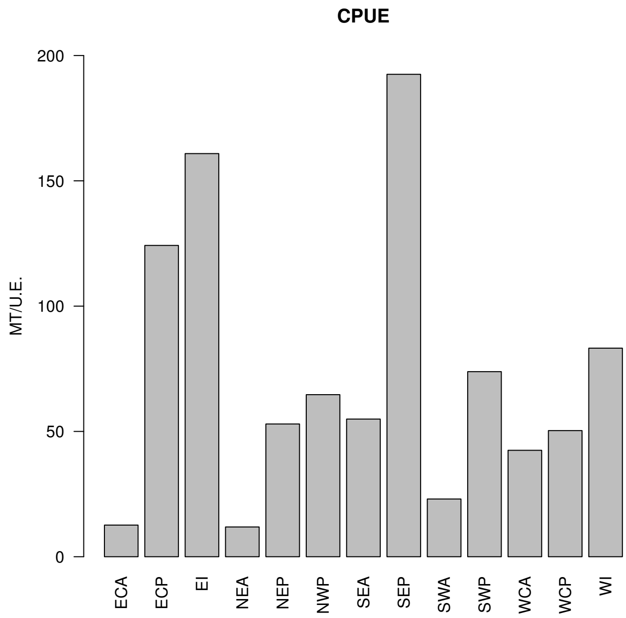


Figure 5.7: Catch per unit of effort (CPUE) distribution

5.2.6 Fresh and frozen tuna commodities: average production, consumption, import, and export

Tuna commodities are grouped into two types of entities: fresh and frozen (ff) commodities (see figure 5.8) and canned or prepared (can) commodities (see figure 5.9). For all tuna species that are represented into the two types of commodities (ff and can), the *tuna* category, that is a mix of several tuna species with an undefined proportion, is separately considered.

The figure 5.8 shows the average volume of production, consumption, import, and export of FF commodities by country for the period 1993-2006. The top producers of FF are obviously the top fishing fleets, i.e., Japan (19%), Taiwan (17%), Indonesia (12%), USA (10%), Spain (9%), Korea (8.8%), etc. Most of the largest producers of FF tuna are also the greatest FF tuna consuming contries, for example, Japan (27%), Korea (16%), and Indonesia (15%). Thailand is the largest consumer and importer of FF tuna, with 31% and 45% of the global consumption and import on average by year, respectively. Its consumption is fed essentially by skipjack with more than 300 thousands tons on average by year. Its FF import products are constituted by yellowfin, skipjack, tuna, and albacore that reach 600 thousands tons on average by year. The remaing FF tuna import volume is shared between Japan (19%), Spain (13%), and USA (7%). The FF tuna export flow is dominated by Taiwan with 37% of the global tuna export on average by year followed by Japan (13%), France (12%), and Spain (10%).

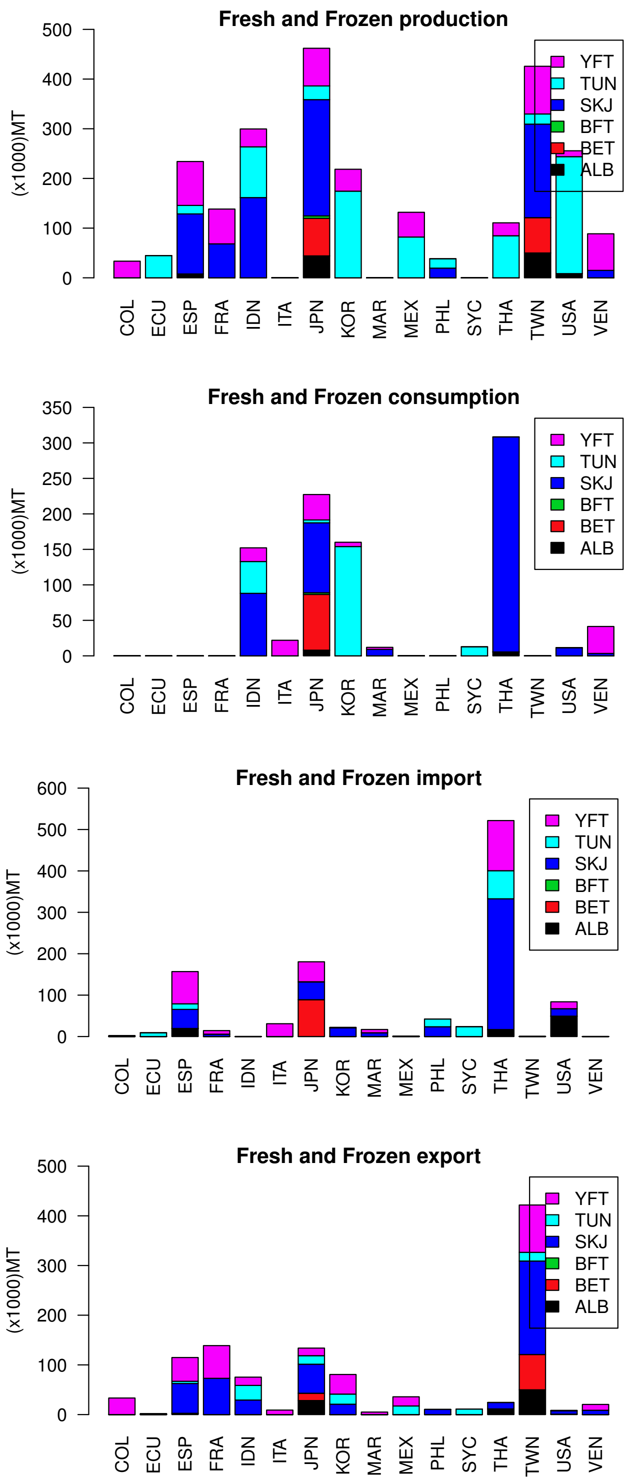


Figure 5.8: Production, consumption, import, and export of FF commodities (mean values for the period 1993-2006)

5.2.7 Prepared tuna commodities: average production, consumption, import, and export

The figure 5.9 shows the average prepared production, consumption, import, and export on average by year for the period 1993-2006. The prepared commodities production is ensured from the production of FF commodities. USA, followed by Spain, is the largest producer of prepared tuna in the world for the period on average. Skipjack, albacore, and *tuna* are the main prepared or canned categories. Skipjack gives the most processing products, while albacore is only prepared by the USA. All others species might be split among the tuna group. The major part of the prepared production is shared between USA (18.8%), Spain (18.7%), Thailand (17%), and Japan (16%). Note that Thailand is the largest producer of prepared tuna for the three last years in the period covered. The three top consumers of canned tuna are USA (30%), Japan (17%), and Spain (12%). The import of prepared products is led by USA (18%), Thailand (18%), UK (15%), and France (14%). Whereas the total export is largely dominated by Thailand (30%), Spain (12%), Ecuador, and France (7%).

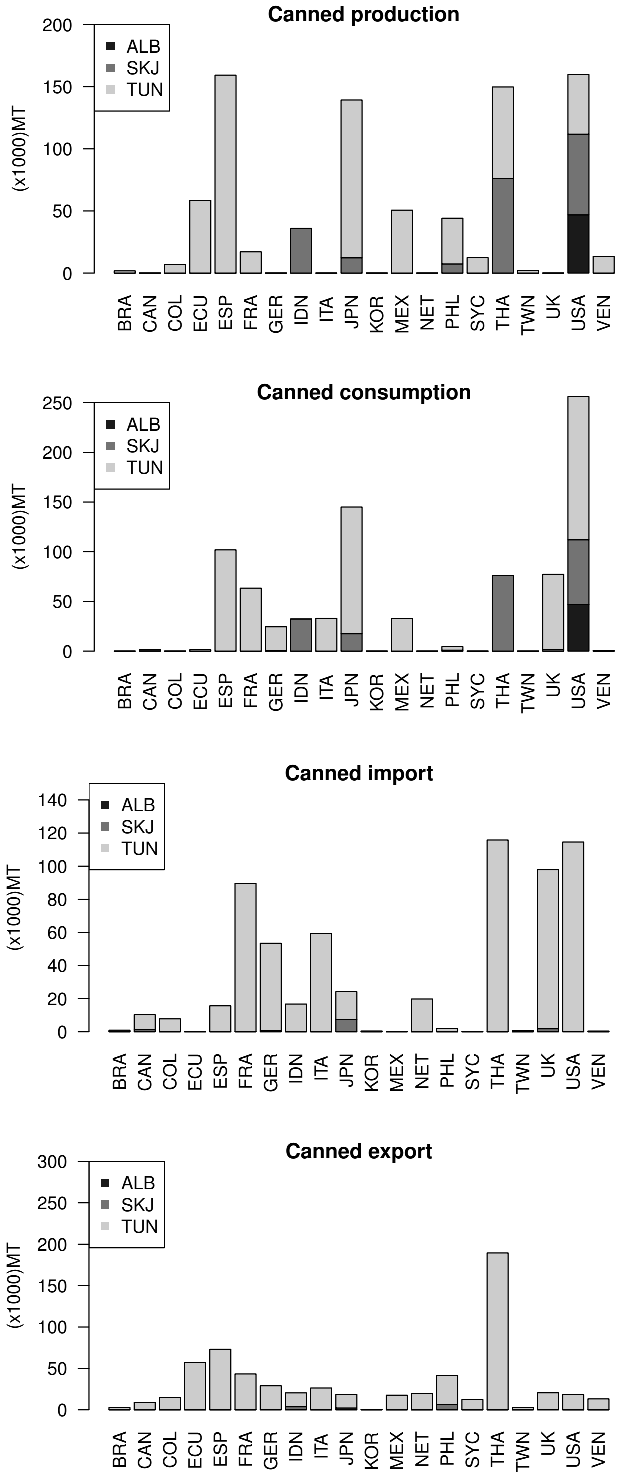


Figure 5.9: Production, consumption, import, and export of prepared tuna (mean values for the period 1993-2006)

5.3 Dynamic analysis

The tuna global commodity chain is also featured by changes observed through time. These change could be observed in tuna catches distributions and trends as well as in the evolution of markets or trade. The network structure by itself is not a stable structure. Any modification of entities directly affects the network. This current section only tries to specially show the dynamics inside the global chain by displaying some maps.

5.3.1 Distribution of catches

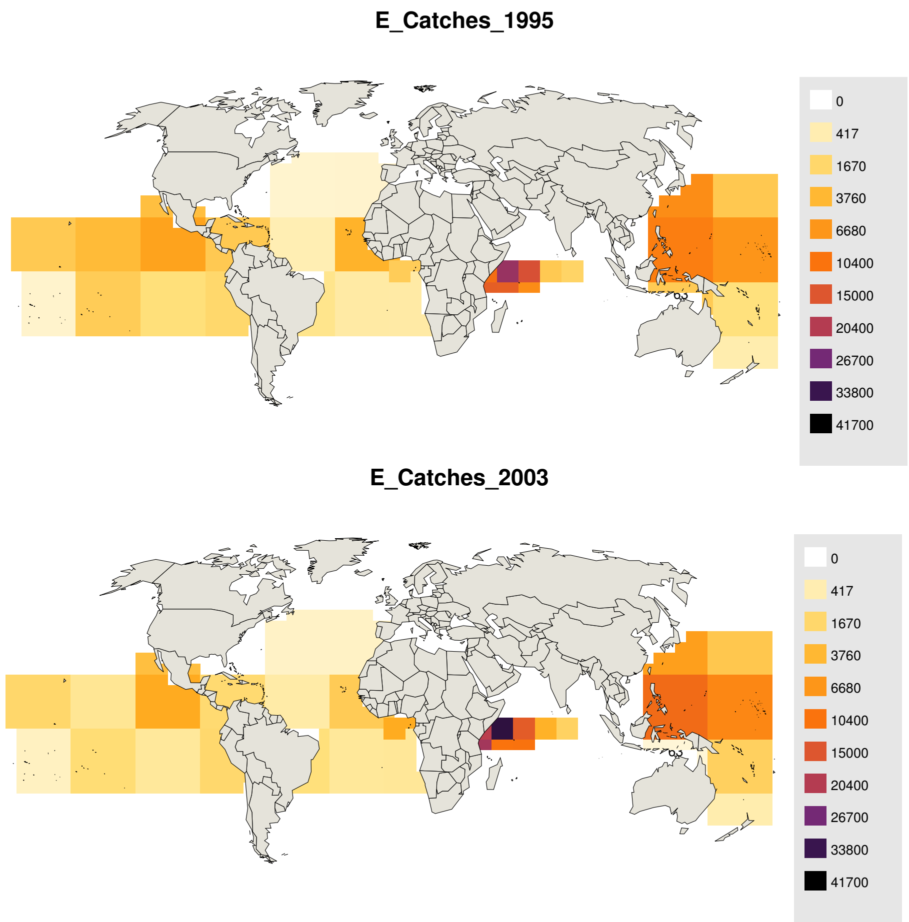


Figure 5.10: Total tuna catches

The figure 5.10 displays the total tuna catches from SARDARA database, for all species, all gears, all countries, and all fishing areas at the beginning and at the end of the considered period. The tuna catches are extended over all the three oceans for the two years. The Atlantic ocean gives the lowest concentration of tuna catches and the higher in the western Indian ocean. In the Pacific ocean, the concentration of tuna catches is relatively high in its central and northern parts.

5.3.2 Trends for the catches distribution by fleet

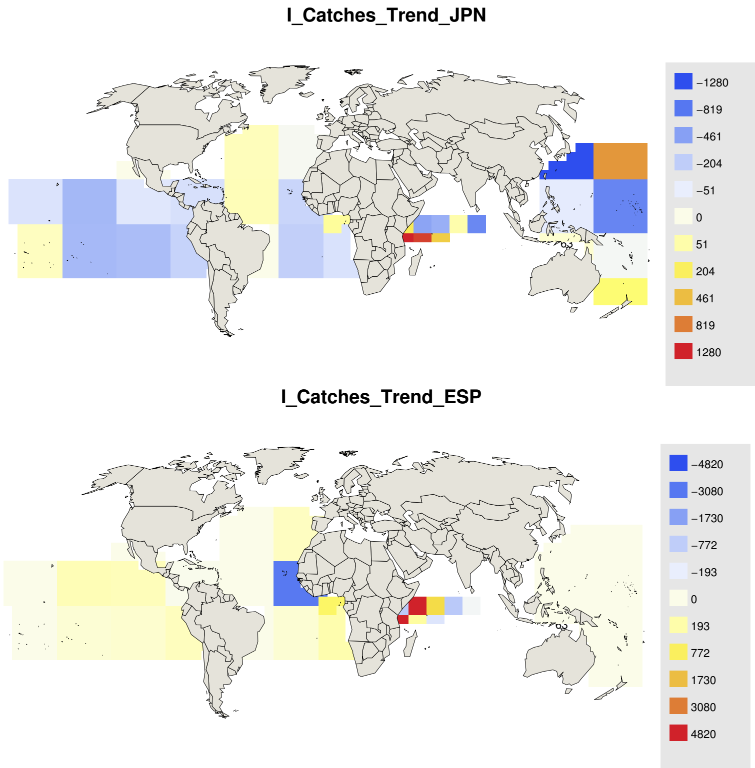


Figure 5.11: Trends in the distribution of catches

The figure 5.11 shows the catches trend for the same period (1993-2006) for two import fleets: the top fleets of Asia (Japan) and European union (Spain). During this period Japan catches were saturated in the Atlantic while increasing between 800 and 1000 tons in the western Indian and the eastern Pacific and decreasing until 1000 tons by quadrat in the western Pacific. For the Spain catches, the trend is different. In the Atlantic ocean catches are decreasing until four thousand tons by quadrat and could reach four thousand tons of increasing in the Indian ocean per small quatrat. The general trend for the both countries remains decreasing catches over the period.

5.3.3 Network of catches distribution by fleet

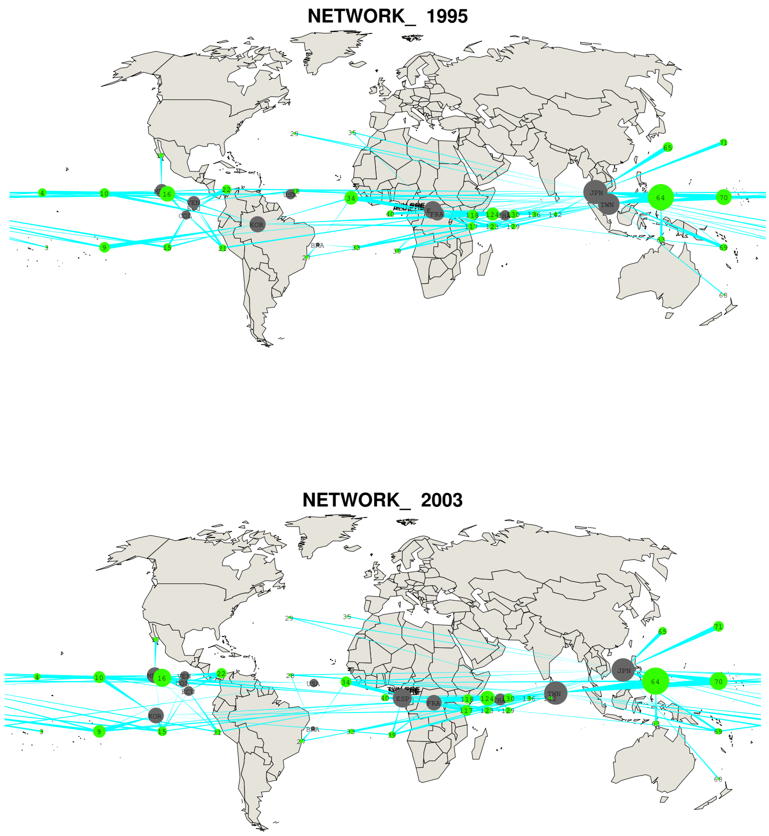


Figure 5.12: Network of catches distribution by fleet

The figure 5.12 displays fleets movement between fishing areas. Fleets remain concentrated in the tropical areas of the three oceans. In general, they harvest tuna, in waters that are the closer than possible to their territory, i.e., in their economic exclusive zones ideally. Korean, Japanese, and Taiwanese fleets are mainly deployed in international waters. Over the period, there was no significant changes. In the Indian ocean, the catch areas are slowly increasing by the opposite to the Atlantic.

5.4 Trade

The trade flows for fresh and frozen, and canned products for all tuna species is detailed in the figures 5.13 and 5.14. These figures describe the market flows between main producers and consumers of fresh and frozen, and canned products. These flows are important to quantify inside the network structure because they could affect the network dynamics. Here only a global view of such trades is shown.

5.4.1 Trade flows: fresh and frozen products

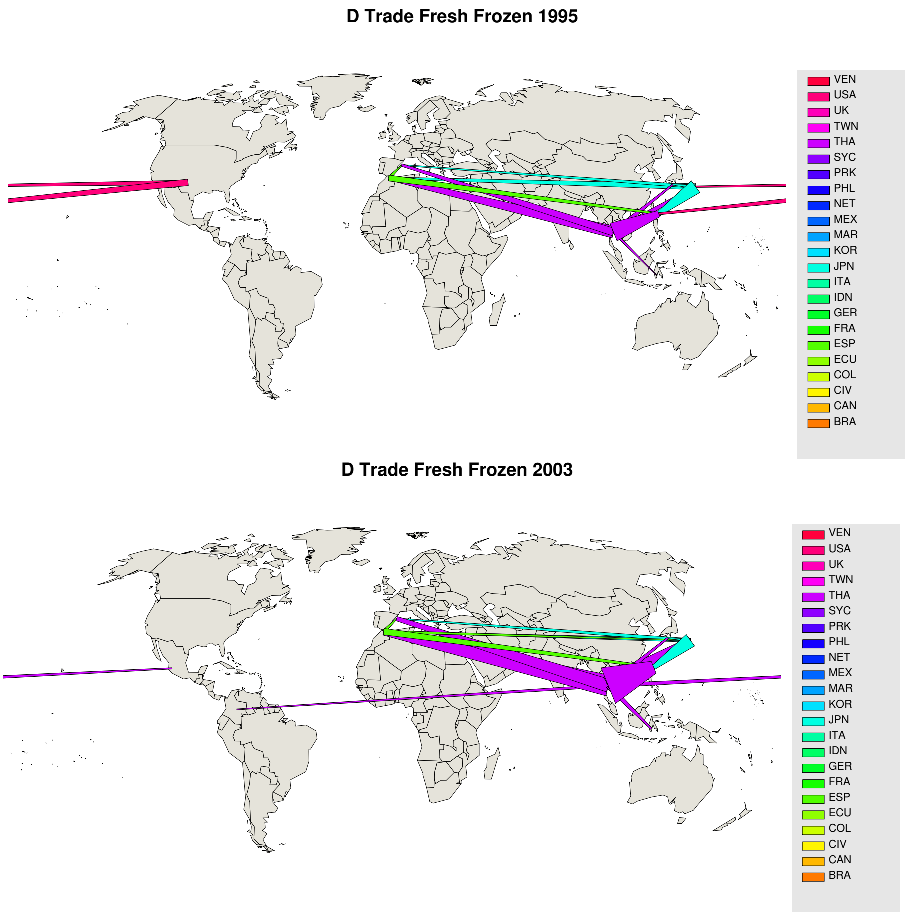


Figure 5.13: Trade evolution for fresh and frozen tuna

The fresh and frozen tuna market is highly influenced by: Japan, Taiwan, Thailand, Indonesia, Spain, USA, Korea, and France (see figure 5.13) and by all targeted tuna species (see figure 5.8). This market is mainly dominated by Japan and Thailand the two largest importing and consuming countries. The former is the main producer of fresh and frozen tuna but imports for its domestic consumption. The latter is the largest importer of FF raw tuna in the world and uses them for the intermediate consumption that consists of more than 95% of skipjack. Japan imports almost the half of its total FF tuna consumption. A great part of its import feed the sashimi market that targets bigeye, yellowfin, and bluefin tuna. Indonesia and Korea are also two important consumming of fresh tuna without a specific preference.

All other countries that evolve in this market could be classified into the exporting countries group. Taiwan leads this group. 70 % of its total catches during 1991-1996 are exported to Thailand (Sun and Hsieh, 2000). These catches consist essentially by skipjack and yellowfin tuna that will be transformed to cannery grade. However, Indonesia intervenes slightly on the exchange through exports but the high level of its consumption could affect the availability of fresh and frozen tuna on this market. This country is known as self sufficient for fresh and frozen tuna.

5.4.2 Trade flows: prepared products

Prepared or canned tuna products are just tuna fresh or/and frozen that are processed. From 1995 to 2003 the exchange flows between countries for prepared commodities are greatly developed. They appear between America(north and south) and some Asian countries. Flows for these products are mainly shared between USA, Spain, Thailand, Japan, France, Venezuela, France, Italy, UK, and Ecuador. Only USA produces and consumes all the three prepared categories (skipjack, albacore, and *tuna*) while only Indonesia and Thailand specifically consume skipjack. Thailand, as the largest exporter in the world, leads this market followed by Spain. Both the export and import flows are mainly constituted by *tuna*. The import flows are dominated by USA, Thailand, and these European countries (France, UK, Germany, Italy, Spain, Netherlands). The former is one of the largest canned tuna producing countries (cf. figure 5.9) while most of European countries remains a net importing country (UK, Germany, Italy, Netherlands...). 70% of the USA canned tuna imports come from Thailand (Sun and Hsieh, 2000).

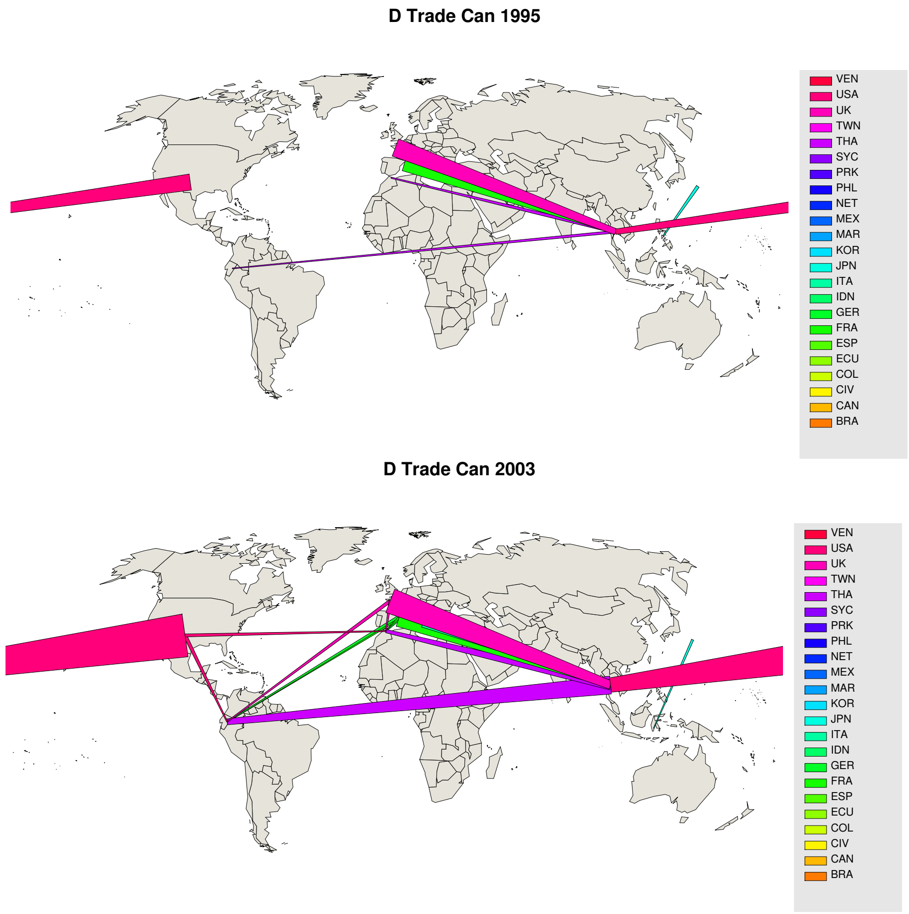


Figure 5.14: Trade evolution for prepared or canned tuna

5.5 Tuna Prices

The tuna prices are a determinant factor of the importance of the tuna commodities on the worldwide tuna markets. Through data used for this work, specifically those from Fishstat database provide both import and export prices for all selected commodities markets. The analysis is done for current price that refers to present price also called the market price. In other words we do not take into account the inflation. The tuna price evolution on both fresh or frozen and prepared commodities markets are displayed for some dominant commodities markets (figure 5.16) and specific tuna commodities (figure 5.15).

On the fresh or frozen commodities markets, Asian countries commodities markets are globally leaders in price for both export and import products. On the prepared commodities markets prices are discussed between Asian, European, and American countries. On average Japanese markets lead on price for skipjack and tuna commodities. Note for both commodities prices curves, missing values take zero (on the abscissa) that means prices at these point are considered as null.

5.5.1 Prices evolution per species

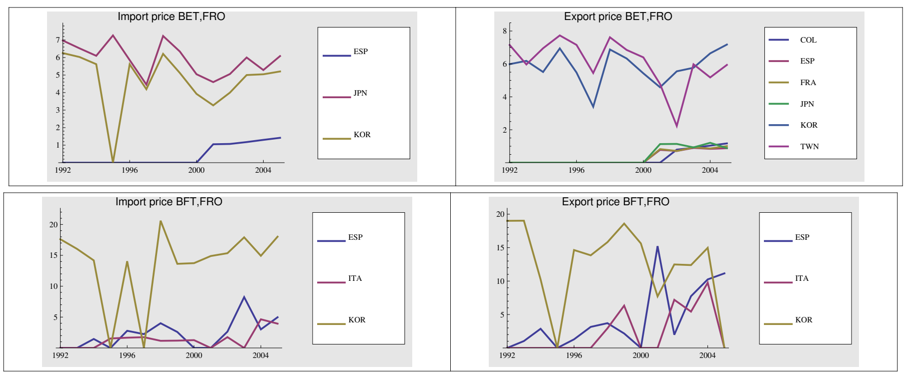


Figure 5.15: Price (current) evolution for bigeye tuna (top) and bluefin tuna (down)

[unit: US dollar per Kg (live weight equivalent)]

The figure 5.15 shows the price evolution for fresh and frozen bluefin (BFT) and bigeye (BET) tuna during the period 1993-2006. These species are generally consumed chilled and destined for the sashimi market (Jiménez-Toribio et al., 2010). The import price for BET is discussed mainly for the Asian markets. Japan leads the price for all this period because its high import volume as previously seen. Taiwan shows the highest export price for the BET followed by Korea for the same reason as the import price. For all the period, the BET import and export prices could reach eight dollars per ton and twenty for the ones of the BFT. Korean market shows the highest prices for the BFT import and export that share with Spain and Italy.

5.5.2 Prices evolution per country

In the figure 5.16 prices observed for the dominant markets for all tuna species (excepted the BFT) and for the two categories are here drawn. Import and export prices are highly influenced by Indonesia and Japan for fresh and frozen tuna. Indonesia shows prices relatively low on average and unstable (from 0.5 to 2 dollars per ton) for the import of ALB, YFT, and SKJ and the export of ALB, YFT, SKJ and TUN. The reason could be the weak participation of this country to exchanges. Japan that exchanges actively shows import prices rather stable for the YFT and SKJ and more fluctuate for the BET for the same period. The reason, skipjack price (ex-vessel) is determined by Thailand (largest importer). For prepared products, the markets considered show prices curves only for the SKP and TUN commodities. These curves for the time period are scattered excepted for the Japanese import where prices shapes have a sense.

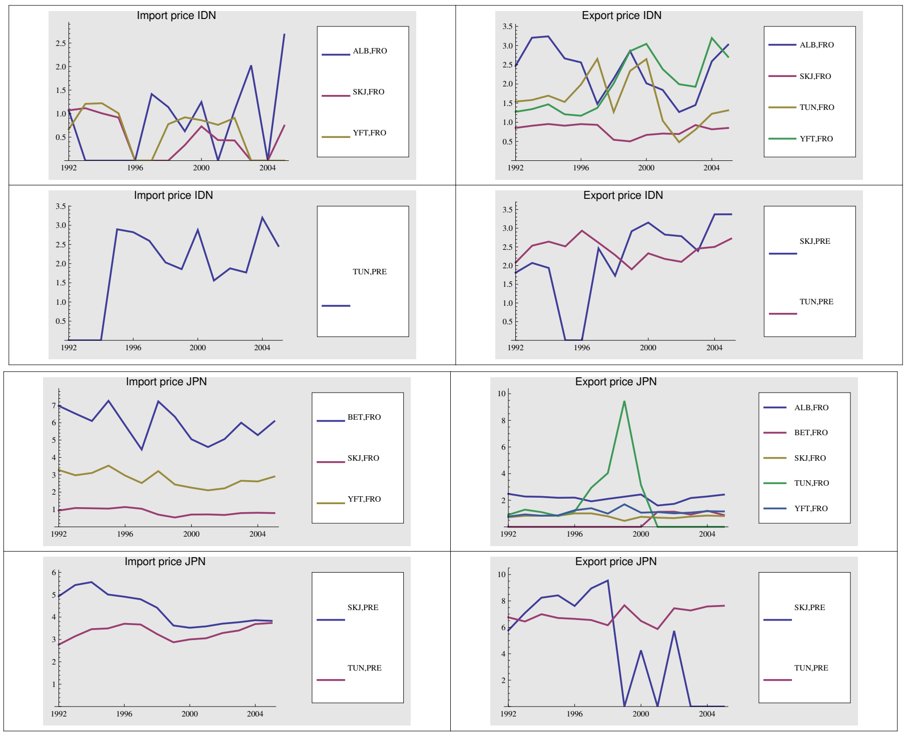


Figure 5.16: Price (current) evolution for Japan and Indonesia [unit: US dollar per Kg (live weight equivalent)]

5.6 The network structure at a country level

The network structure for the tuna chain for a country has been already described in the previous chapter. The structure starts with catch of tuna species until the final consumption fresh or frozen and canned products. In the figure 5.17 emphasis is put on some countries presenting significant facts on their network structure. Japan and Indonesia are both large producing and consuming countries of FF tuna.

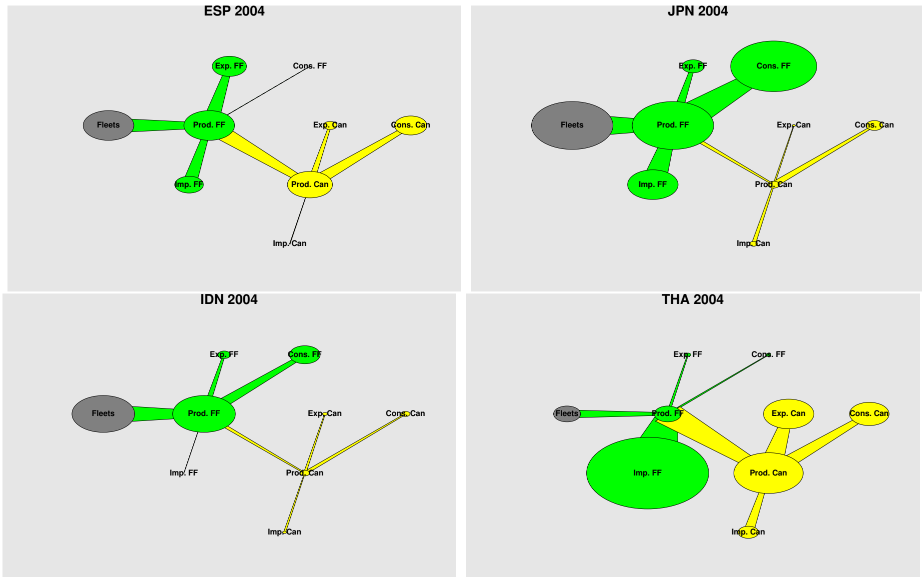


Figure 5.17: The network structure by country in the end of period

Note that Taiwan (as seen previously) is not only an important producer but also a large exporting country of FF products. By the opposite to Indonesia that is self-sufficient for these products, Japan needs import to feed its domestic consumption and participate lowly to the canned production. Spain and Thailand influence the network structure for both FF and canned tuna products. They are both producing and consuming countries of canned tuna. The former produces FF tuna to feed the canning production. Its production is essentially used to fill the domestic consumption. The latter imports FF tuna for the canning production. The major part of its production is exported elsewhere.

5.7 Conclusion

Description of all entities that characterize the network structure as well as the significant facts inside the network have been showed. Tuna markets have been highlighted through import and export flows (volume and value). Sharing price on these markets provide some rough information on the market operators.

The FF market is greatly influenced by Japan, Taiwan, Korea, and Indonesia while the canned market is dominated by Thailand, Spain, Italy, and USA. The influence can be viewed through the volume, consumed (Indonesia, Japan, USA...), exported (Taiwan, Thailand...), and imported (Japan, Thailand, France, Korea...). It can be also viewed through the value or the prices.

On the FF market, the bluefin tuna showed the highest price for the period compared to fresh and frozen yellowfin and bigeye tuna. They are all destined to the sashimi market in Tokyo, Japan. Fresh and frozen bluefin tuna are considered as luxury goods. Sun and Chiang (2010) computed the flexibility for these products that are less than unity that means an increase of 1 % in the supply of all sashimi grade tuna species could lead to a decrease of the bluefin tuna prices less than 1%. They affirm that: "*the Japanese consumers are willing to pay the premium price for high-quality fresh and frozen bluefin tuna than for other tuna species*".

The bangkok market represents the most important market for cannery grade tuna that targets yellowfin and skipjack tuna. Both sashimi grade (Tokyo) and cannery grade (Bangkok) markets are competitive and strongly integrated into the world market (see Jeon et al. (2008)). Note that the global tuna market includes the Americas, American Samoa, Bangkok (Thailand), Abidjan (Ivory coast), Europe (Spain and Italy), Tokyo (Japan). All these markets can not be deeply studied due the availability of data. But the global analysis provided a good understanding of the system.

Finally, the originality of this work remains in the consideration of the global fisheries and markets through the dynamic network context. The hypothesis of a dynamic network structure for the global tuna commodity chain is plausible. This structure will be very useful for the implementation of the global tuna chain model in the economic globalization context.

Part IV

Towards a model of the global tuna commodity chain

The model: an introduction

The current part aims to present a model of the global tuna commodity chain. This model is designed in order to analyze the main stakes that currently face tuna fisheries systems as well as markets. Among them, diverse present issues influence the goal of the model such as: the over exploitation of large pelagic stocks that lead to their threat (Myers and Worm, 2003; Majkowski, 2007), the economic globalization that affects the economics of fleets and tuna markets (Catarci, 2005; Pauly et al., 2005), and the increasing demand of tuna products as well as the structural changes in the demand for tuna (Jeon et al., 2008; Jiménez-Toribio et al., 2010) that affect both tuna stocks and markets. The global control of tuna exploitation is then viewed as a possible solution.

The fact is, most part of the tuna is caught offshore, out of Exclusive Economics Zones (EEZ) by long distance fleets (Reid et al., 2003). Tuna products are also consumed worldwide, either fresh, frozen or prepared. We may consider that there is a global market for tuna (Jeon et al., 2008; Jiménez-Toribio et al., 2010; Catarci, 2005). The management of tuna fishing capacity implies international cooperation (Bayliff, 2004). That is initiated with specialized international commissions in main oceans: Atlantic, Pacific, and Indian.

The analysis of such systems relies on the idea of a global commodity chain (Gibbon, 2001; Gereffi et al., 2001) The modeling approach used, follows the same way as the commodity chain relating small pelagic fisheries and the global fishmeal and fish oil markets (Mullon et al., 2009; Merino et al., 2010).

The formalism of network economics, and specifically the variational inequality approach (Nagurney, 1993; Nagurney et al., 2002; Mullon, 2013) are applied to the study of the equilibrium and the dynamics of a global supply chain. The originality of this model results in the insertion of scenarios that define the global tuna commodity chain.

Scenarios about the future of a global system

The scenario oriented modeling approach is used. It differs to a prediction oriented approach. Building of scenarios is the main purpose of the approach. Here are the scenarios to be tested.

- *Collapse of fresh market*: what could happen if, following a sanitary problem, there is a huge decrease of the demand for fresh tuna (Bestor, 2004)?
- *Increase of oil price*: what could happen if, due to the decrease of supply, there is huge increase of oil prices, affecting both fishing costs and shipment costs (Tyedmers, 2004; Tyedmers et al., 2005)?
- *Trade regulation*: what could happen if, in the continuity of these last years, there is a decrease of importation taxes for all tuna commodities (Grafton et al., 2010)?
- *Climate change and productivity*: what could happen if, due to present climate changes, productivity of marine areas changes dramatically, high or low (Brander, 2007; Cheung et al., 2010)?
- *Offshore marine protected areas*: what could happen if, a beginning of a global governance of tuna fisheries is set up and results in the application of a system of marine protected areas (Scovazzi, 2004; Hyrenbach et al., 2000)?
- *Moratorium on fishing aggregative devices*: what could happen if, in the framework towards a global governance, it is decided to prohibit fishing aggregative devices for some years, affecting catchability (Ménard et al., 2000)?

We have in mind the necessity of developing these scenarios when building the model. This is an important feature which allows determining scales, process, interactions, and all choices that are key issues in the modeling of complex systems.

The organization of this part is as follows: The bioeconomic model for the GTCC is developed in the chapter 6. The process followed for the calibration data and parameters associated to the model is explained throughout the chapter 7 and more details as data and computation results are provided in the appendix A as complement to this chapter. Finally, the way to implement numerically the model is explained in chapter 8 with supplement material in support to this chapter is found in the appendix B.

Chapter 6

Model the GCCC and its dynamics

Contents

6.1 Introduction

We have previously got a global view about the tuna commodity chain from the tuna stocks to tuna markets using existing statistics concerning stocks (catches, biomass), fleets (effort, fishing capacity, investment behavior), markets (volumes, prices). The tuna commodity chain has been pictured in a network structure. The model that is intended to build here is based on this structure. The current chapter aims, by recalling first all entities featuring the network structure of the tuna commodity chain, to explain the methodology used for designing the model. In the following sections the materials and methods applied to the model are developed.

6.2 Network structure

6.2.1 Basic entities of the network

Five types of entities are already selected within the structure of the global chain. Recalling them: oceanic areas a, tuna species e, fishing, producing, and consuming countries p, q, fresh and/or frozen commodities f, and canned or prepared commodities c. All these entities are described and summarized in the table 6.1.

Table 6.1: Entities

Type	Symbol	Entities
Areas	a	33 fishing areas; see figure 4.1.
Species	e	albacore (ALB), bigeye Tuna (BET), bleufin Tuna (BFT), yellow fin (YFT), skipjack (SKJ); see figure 5.1.
Countries	p, q	Brazil (BRA), Canada (CAN), Columbia (COL), Ecuador (ECU), Spain (ESP), France (FRA), Germany (GER), Indonesia (IDN), Italy (ITA), Japan (JPN), South Korea (KOR), Morocco(MAR), Mexico (MEX), Netherlands (NET), Philippines (PHL), Seychelles (SYC), Thailand (THA), Taiwan (TWN), United Kingdom (UK), United States (USA), Venezuela (VEN).
Fresh, frozen commodities	f	Albacore fresh (ALB-FRE), Albacore frozen (ALB-FRO), Bigeye tuna frozen (BET-FRE), Bigeye tuna fresh (BET-FRO), Skipjack fresh (SKJ- FRE), Skipjack frozen (SKJ-FRO), Bluefin fresh (BFT-FRO), Yellowfin tuna fresh (YFT-FRE), Yellowfin tuna frozen (YFT-FRO), Tuna fresh (TUN-FRE), Tuna frozen (TUN-FRO)
Canned commodities	c	albacore prepared (ALB-PRE), skipjack prepared (SKJ-PRE), tuna prepared (TUN-PRE)

6.2.2 Network entities

The model follows the network structure characteristics. The network components such as nodes, links, and flows are crucial in the model description. The global commodity chain for tuna is represented as a network in figure 6.1. The several types of nodes and links showed could be taken as a prototype of the model in figure 6.1 (top) and all notations for nodes and links are also showed (down). In this directed graph representation, adjacent nodes are all linked by arrows, following the same directions from fish population to fish markets (as already seen). Description and characteristics of each node and link are detailed below. Detailing information throughout this section is important before developing the model because they will serve to the model formulation.

6.2.3 Nodes

We distinguish three kinds of nodes: producers, transformers, wholesalers (see appendix 6.4). Eight types of nodes are defined for this structure (see figure 6.1). All nodes are distinguished by a specific price. Their main features are described below and then summarized in the table 6.2.

Fish populations They correspond to an area a and a species e, are denoted (a, e). They are defined by the tuna population biomass (the stock value) S_{ae} and other biological characteristics such as the environmental carrying capacity K_{ae}, the intrinsic growth rate of stocks r_{ae}, and the catchability coefficient q_{ae}. The fish populations node is considered inside the network as the only producer of the structure. The node price is qualified by the fishing price also called the access price P_{ae}.

National fleets They are represented by both a targeted species e and a country p. That does not mean a fleet could only target one tuna species. The node fleet is denoted (p, e) with P_{ep} the species price. Fleets are characterized by their fishing capacity V_{ep}, a depreciation rate of the invested capital η_{ep}, and an investment rate σ_{ep}. The relationship that links these components will be presented later. The fleets node, as an intermediate node, belongs to the transformer nodes and is constrained

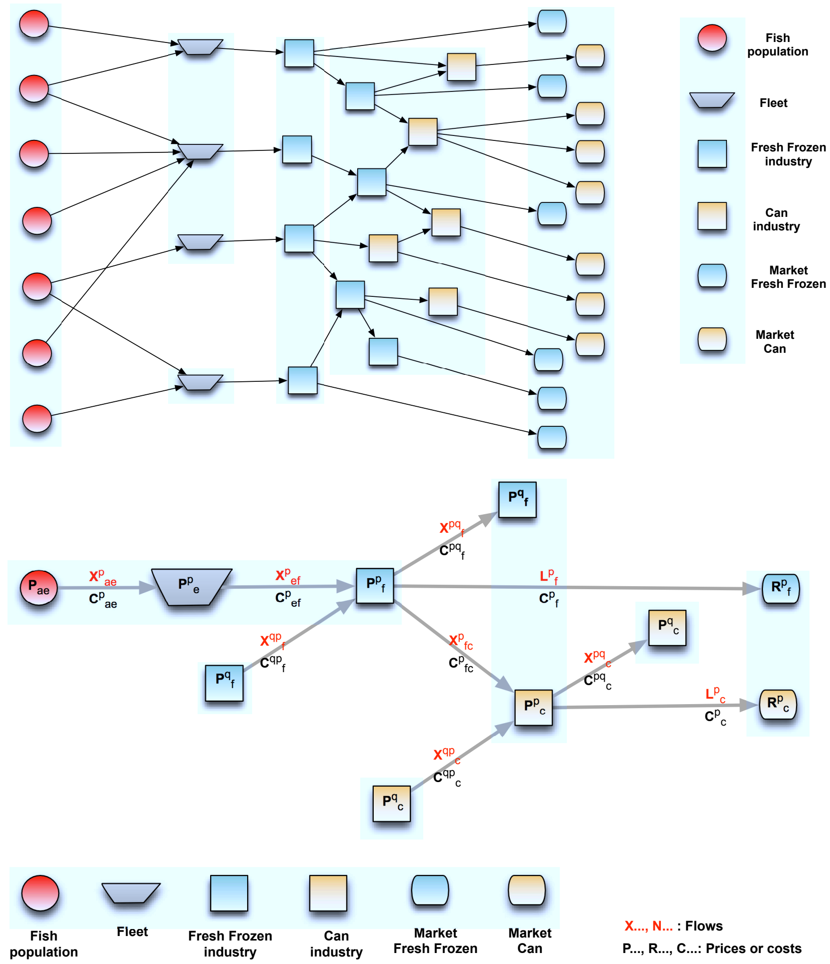


Figure 6.1: Nodes and links of the tuna commodity chain

by the fishing capacity.

National commodities trade and production systems They differ for the both types of commodities. (1) Fresh or frozen commodities trade and production systems are given by a country p and a fresh or frozen commodity f. They are denoted (p, f). The production node with the price P_{fp} is a transformer node but are not subjected to any constraint. Whereas, the fresh and frozen traded nodes denoted P_f^q (import and export prices) are terminal nodes. They are neither transformers nor constrained nodes. (2) Canned commodities production systems are given by a country p and a canned commodity c. They are denoted (p, c) and characterized by their production capacity U_{cp}, a depreciation rate η_{cp}, and an investment rate σ_{cp}. They are a transformer node denoted P_{cp} and limited by the production capacity constraint. The canned commodities trade is defined by both import and export nodes denoted P_{cq}.

National commodities markets Each commodities market is defined through both a country and a type of commodities. (1) National fresh or frozen commodities markets are defined by a country p and a fresh commodity f. They are denoted (f, p) and characterized by an inverse demand function relating prices R_{fp} to volumes L_{fp} according to the relationship $R_{fp} = a_{fp} - b_{fp}L_{fp}$. (2) National canned commodities markets are described by a country p and a canned commodity c. They are denoted (c, p) and characterized by an inverse demand function R_{cp} to volumes L_{cp} with $R_{cp} = a_{cp} - b_{cp}L_{cp}$. The both types of commodities markets are viewed as the two terminal nodes of the network structure (see figure 6.1) and are the both wholesalers nodes.

Table 6.2: Entities and their characteristics: Nodes

Node	Kind	Characteristics	Number of entities in network
Fish populations (a, e)	Producer	Stock S_{ae}, fishing price P_{ae}	95
National fleets (p, e)	Constrained Transformer	Species prices P_{ep}, fishing capacity V_{ep}, depreciation rate η_{ep}, investment rate σ_{ep}	35
National FF commodities production systems (p, f)	Transformer	FF production price P_{fp}	103
National canned commodities production systems (p, c)	Constrained Transformer	Canned production price P_{cp}, Production capacity U_{cp}, depreciation rate η_{cp}, investment rate σ_{cp}	36
FF commodities trade (p, f)	Import/export	Import/ export price P_f^q	
Canned commodities trade (p, c)	Import/export	Import/ export price P_{cq}	
National FF commodities markets (f, p)	Wholesaler	Inverse demand function $R_{fp} = a_{fp} - b_{fp}L_{fp}$	15
National canned commodities markets (c, p)	Wholesaler	Inverse demand function $R_{cp} = a_{cp} - b_{cp}L_{cp}$	14

6.2.4 Links

According to the network theory, the exchange of flows between two adjacent nodes is possible with a link. The seven types of links that hold the network structure are described below and then summarized in the table 6.3. Their localization inside the network structure can be also viewed in the figure 6.1.

Catches flows The links between a fish population and a fishing fleet (country) is assigned by: $(a, e) \to (p, e)$. Flows are here the catches level and denoted X_{aep}. These links are characterized by the exerted fishing effort E_{aep} and the fishing costs C_{aep}, that is the cost of fishing one ton of tuna. The standardized fishing effort is limited according to the fishing capacity of fleets: $\sum_a E_{aep} \leq V_e^p$. We get constraints in terms of flows: $\sum_a X_{aep}/q_{ae}^p S_{ae} \leq V_e^p$. The costs of catches flows will be detailed and estimated in the calibration section.

Transformation flows for species The transformation flows of a caught tuna into a fresh or frozen commodity are distinguished by $(p, e) \to (p, f)$. Flows are denoted X_{efp} and characterized by transformation costs C_{efp}. These costs will be neglected in this study. For fresh and frozen tuna, these costs are well existent and traduced by the conservation costs, transport and so one. If for fresh tuna these costs could be low, for frozen commodities they could be high and significant including freezing costs (see thèse remi).

Transformation flows of a fresh or frozen commodity The transformation flows of a fresh or frozen commodity into a canned commodity are given by $(p, f) \to (p, c)$. Flows are denoted X_{fcp} and characterized by both a transformation cost: C_{fcp} (including cannery costs) and a transformation ratio: $\rho \simeq 2$. These flows are limited by a physical constraint due to canning capacity: $\sum_f X_{fcp} \leq U_{cp}$.

Trade flows between countries These flows exist for the both type of commodities. (1) Trade flows of fresh, frozen commodities between countries are written $(p, f) \to (q, f)$. Flows are denoted X_{fpq} and characterized by trading costs C_{fpq}. (2) Trade flows of canned commodities between countries take the form $(p, c) \to (q, c)$.

Flows are denoted X_{cpq} and marked by trading costs C_{cpq}. For the both types of commodities the trading costs include the transport costs, taxes, and duties.

Consumption of commodities The production systems are connected to the consumption systems by this kind of links: $(p,f) \to (f,p)$ for the consumption of a fresh or frozen commodity and $(p,c) \to (c,p)$ for the consumption of a canned commodities. Flows are denoted L_{fp} for the former and L_{cp} for the latter. The selling costs C_{fp} (for FF tuna) and C_{cp} (for canned tuna) related to these links will be neglected.

Table 6.3: Entities and their characteristics: Links

Link	Flows	Characteristics	Number of entities in network
Catches $(a,e) \to (p,e)$	X_{aep}	C_{aep}	211
Catches to FF commodities $(p,e) \to (p,f)$	X_{efp}	C_{efp}	53
Production of canned commodities $(p,f) \to (p,c)$	X_{fcp}	C_{fcp} (including cannery costs)	36
Trade of FF commodities between countries $(p,f) \to (q,f)$	X_{fpq}	C_{fpq} (including transport costs and taxes)	176
Trade of canned commodities between countries $(p,c) \to (q,c)$	X_{cpq}	C_{cpq} (including transport costs and taxes)	115
National consumption FF commodities $(p,f) \to (f,p)$	L_{fp}	C_{fp}	15
National consumption of canned commodities $(p,c) \to (c,p)$	L_{cp}	C_{cp}	14

6.3 Modeling principle

The global commodity chain model for tuna species is described through a dynamic structure. The modeling process meets two stages:

- At time t, setting the values of parameters. Each parameter is known to link to a scenario. Hence, we define the values of parameters according to scenario, then compute the economic equilibrium of the system: (fishing capacity, stocks, demand, costs, parameters) $\to$ (catches, sales, prices).

- From time t to time $t+1$, we compute the new state of the system according to the production and investment functions: (catches, sales, prices, costs, fishing capacity, parameters) $\rightarrow$ (stock, income, fishing capacity, prices).

6.4 The network equilibrium of commodity chains

The methods we use here to compute the equilibrium are relevant to the network economics of a commodity chain. For many more details see Nagurney et al. (2002); Nagurney (2006); Mullon (2013). In the following section, we base our analysis on Mullon (2013)'s presentation.

6.4.1 Notations

The network structure of a commodity chain is given in figure 6.1. Nodes $n \in N$ represent agents: they can be producers ($p \in P$), transformers ($g \in G$), wholesalers ($d \in D$). Links $l \in L$ represent flows between agents; we denote $o(l)$ the origin and $d(l)$ the destination of a link. We define usual incidence functions: $\delta^o_{nl} = 1$ if $o(l) = n$, $\delta^d_{nl} = 1$ if $d(l) = n$

Characteristics of a link $l \in L$ are: (1) commodity flow X_l, (2) transportation costs C_l.

Characteristics of a node $n \in N$ are: (1) ingoing flow $I_n = \sum_l \delta^d_{nl} X_l$, (2) outgoing flow $O_n = \sum_l \delta^o_{nl} X_l$ and (3) commodity price P_n. For a wholesaler $n \in D$, we have a price/quantity relationship $P_n = F(I_n)$; we use $P_n = a_n - b_n I_n = a_n - b_n \sum_{n,l} \delta^d_{nl} X_l$; parameters a_n and b_n are given. For a transformer $n \in G$, P_n results from market equilibrium. For a producer $n \in P$, P_n equals production costs (given). For some nodes, there are capacity constraints of type: for $q \in Q \subset G \subset N$, $\sum_l \delta^d_{ql} f_{ql} X_l \leq g_q$ ($f_{ql} \geq 0$). To such a constraint q , we associate a shadow price λ_q.

Given a state $Z = ((X_l), (P_n))$, we consider, at a node $n \in G$, $E_n(Z)$ the difference between ingoing flows and outgoing flows, and at a link $l \in L$, the difference of

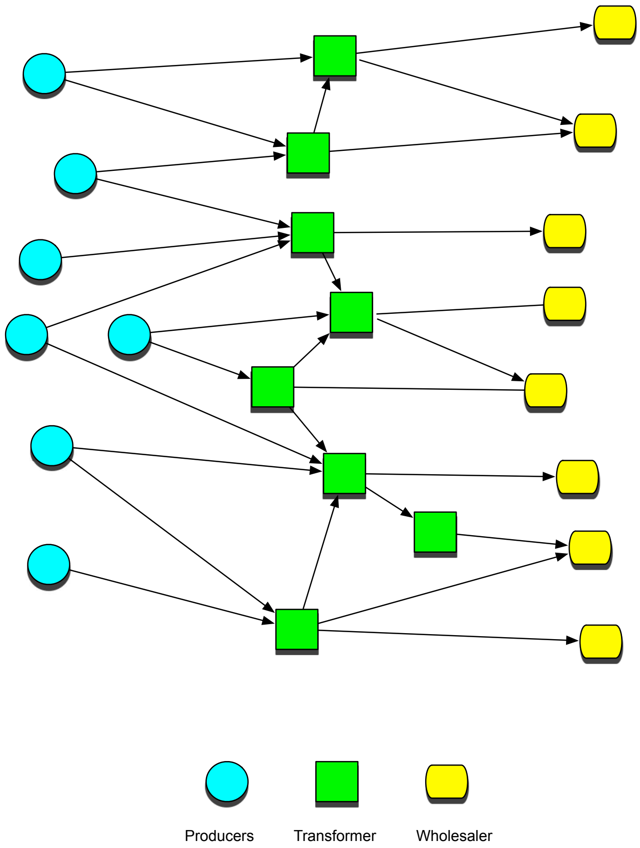


Figure 6.2: A commodity chain

costs $A_l(Z)$:

$$\begin{aligned} E_n(Z) &= \sum_l (\delta^d_{nl} - \delta^o_{nl}) X_l \\ A_l(Z) &= P_{o(l)} - P_{d(l)} - C_l = \sum_n (\delta^o_{nl} - \delta^d_{nl}) P_n - C_l \end{aligned}$$

A state of the system is $Z = ((Xl), (P_n), (\lambda_q)) \in R_+^{N_L} \times R_+^{N_G} \times R_+^{N_Q}$. We define functions $A_l(Z)$ and $E_m(Z)$ as before. We put $D_q(Z) = g_q - \sum_l \delta^d_{ql} f_{ql} X_l$. We put $B_l(Z) = A_l(Z) + F_l(Z)$ where $F_l(z) = \sum_q \delta^q_{ql} f_{ql} \lambda_q$. Constrained set $H \subset R_+^{N_L} \times R_+^{N_G} \times R_+^{N_Q}$ is defined by condition : $D_q(Z) \geq 0$.

6.4.2 Equilibrium definition

A network equilibrium is a state $Z^* = \big((X_l^*), (P_n^*), (\lambda_q^*)\big) \in H$ such that : (1) For all transformers, either ingoing flow is greater than outgoing flow and there is no price; or : ingoing flow equals outgoing flow and there is a price; (2) For all links l such that there is no constraint on their destination, either price at origin plus transportation cost is greater than price at destination and there is no flow; or price at origin plus transportation cost equals price at destination and flow is smaller than capacity. (3) For all constrained transformers, constraints are satisfied and the associated shadow price is positive only if constraints are exactly satisfied. In other words:

Definition 6.4.1 *A network equilibrium is a state $Z^* = \big((X_l^*), (P_n^*), (\lambda_q^*)\big) \in H$ such that :*

- *For all transformers $n \in G$, either $P_n^* = 0$ and $E_n(Z^*) \geq 0$; or : $P_n^* > 0$ and $E_n(Z^*) = 0$;*
- *For all links l such that $d(l) \notin Q$, either $X_l^* = 0$ and $A_l(Z^*) \geq 0$; or $0 < X_l^*$ and $A_l(Z^*) = 0$;*
- *For all transformers $q \in Q$, : $D_q(Z) \geq 0$; for all $l \in L$ such that $q = d(l) \in Q$, either $X_l^* = 0$ and $A_l(Z^*) \geq \lambda_q^*$, or $0 < X_l^*$ and $A_l(Z^*) = \lambda_q^*$; moreover $\lambda_q^* = 0$ if $D_q(Z^*) > 0$.*

6.4.3 Equilibrium characterization

Let us consider the functional $F : H \to R^{N_L} \times R^{N_G} \times R^{N_Q}$ defined by $F(Z) = ((B_l(Z), E_n(Z), D_q(Z))$. We have:

Theorem 6.4.2 *$Z^* \in H$ is an equilibrium state of the system if and only if it is a solution of the variational inequality $VI(F, H)$: find $Z^* \in H$ such that for all $Z \in H$, $(Z - Z^*).F(Z^*) \geq 0$*

Proof: Let us prove that if $Z^* = \big((X_l^*), (P_n^*), (\lambda_q^*)\big) \in H$ is an equilibrium state, it is a solution of the variational inequality. We write:

$$(Z - Z^*).F(Z^*) = \sum_l (X_l - X_l^*) B_l(Z^*) + \sum_n (P_n - P_n^*) E_n(Z^*) + \sum_q (\lambda_q - \lambda_q^*) D_q(Z^*)$$

Just as before, we have:

$$\sum_l (X_l - X_l^*)A_l(Z^*) + \sum_n (P_n - P_n^*)E_n(Z^*) \quad \geq \quad 0$$

Remains to prove that

$$S = \sum_l (X_l - X_l^*)F_l(Z^*) + \sum_q (\lambda_q - \lambda_q^*)D_q^*(Z) \quad \geq \quad 0$$

We have :

$$\begin{aligned}
S &= \sum_l (X_l - X_l^*) \sum_q \delta_{ql}^q f_{ql} \lambda_q^* + \sum_q (\lambda_q - \lambda_q^*)D_q^*(Z) \\
&= \sum_q \lambda_q^* \sum_l (X_l - X_l^*)\delta_{ql}^q f_{ql} + \sum_q (\lambda_q - \lambda_q^*)D_q^*(Z) \\
&= \sum_q \lambda_q^*(D_q(Z) - D_q^*(Z)) + \sum_q (\lambda_q - \lambda_q^*)D_q^*(Z) \\
&= \sum_{q|\lambda_q^*=0} \left[\lambda_q^*(D_q(Z) - D_q^*(Z)) + (\lambda_q - \lambda_q^*)D_q^*(Z)\right] \\
&\quad + \sum_{q|\lambda_q^*>0} \left[\lambda_q^*(D_q(Z) - D_q^*(Z)) + (\lambda_q - \lambda_q^*)D_q^*(Z)\right] \\
&= \sum_{q|\lambda_q^*=0} \lambda_q D_q^*(Z) + \sum_{q|\lambda_q^*>0} \lambda_q^* D_q(Z) \\
&\geq 0
\end{aligned}$$

Let us prove that if $Z^* = ((X_l^*), (P_n^*), (\lambda_q)) \in H$ is a solution of the variational inequality, it is an equilibrium state. Suppose that Z^* is not an equilibrium. In the definition 6.4.1 of the economic equilibrium, negation of (1) and (2) leads to a contradiction, just as before. Negation of (3): we will consider Z identical to Z^* except $X_l = X_l^* + \varepsilon D_q(Z^*)$ and $\lambda_q = \lambda_q^* + \eta$; then $(Z - Z^*).F(Z^*) = (X_l - X_l^*)B_l(Z^*) + (\lambda_q - \lambda_q^*)D_q(Z^*) = \varepsilon(A_l(Z^*) + F_l(Z^*)) + \eta D_q(Z^*)$; we have to check:

- If $D_q(Z^*) < 0 :$ we consider $\varepsilon = 0$ and $\eta = 1$.

- If $D_q(Z^*) = 0$, $d(l) = q$, $X_l^* > 0$ and $A_l(Z^*) \neq \lambda_q^* :$ we consider $\varepsilon = 1$ and $\eta = 1$.

- If $D_q(Z^*) > 0$, $d(l) = q$, $:$ we consider $\varepsilon = 0$ and $\eta = 1$.

Theorem 6.4.3 *F is an affine function: $F(Z) = M.Z + N$ with vector N and matrix M defined as follows $N_l = -C_l - \sum_{n \in P} \delta^o_{nl} C_n + \sum_{n \in D} \delta^o_{nl} a_n$, $N_q = g_q$, $M_{ll'} = \sum_{n \in D} (\delta^d_{nl'} \delta^d_{nl}) b_n$; $M_{ln} = \delta^o_{nl} - \delta^d_{nl}$. $M_{lq} = \delta^d_{ql} f_{ql}$.*

$$M = \begin{pmatrix} M_{LL} & M_{LN} & M_{LQ} \\ -^T M_{LN} & 0 & 0 \\ -^T M_{LQ} & 0 & 0 \end{pmatrix} \quad , \quad N = \begin{pmatrix} N_L \\ 0 \\ N_Q \end{pmatrix}$$

6.5 The network equilibrium of the GCCC

Now, we make explicit the previous complementarity principles in the case of the global commodity chain for tuna. Recall notations. Areas are denoted a, species e, countries p, fresh commodities f, can commodities c. Stocks are denoted ae, fleets ep, fresh commodity transformers fp, can producers cp, fresh markets fm, can market cm. At the beginning of a time step, the system is characterized by the following parameters:

- production costs $(C_{ap,ep}, C_{ep,fp}, C_{fp,cp})$. They are all costs linked to intermediate nodes and some of them depend on fish stocks,

- transportation costs $(C_{fp,fq}, C_{cp,cq}, C_{fp}, C_{cp})$. They are all costs linked to terminal nodes,

- fishing and canning capacities V_{ep} and U_{cp}, already described and defined the production system,

- a relationship between quantities and prices on markets: $R_{fp} = a_{fp} - b_{fp} L_{fp}$ and $R_{cp} = a_{cp} - b_{cp} L_{cp}$.

Then a state of the system is made of:

- flows on all links $X = (X_{ap,ep}, X_{ep,fp}, X_{fp,cp}, X_{fp,fq}, X_{cp,cq}, L_{fp}, L_{cp})$

- prices on intermediate nodes, in other words excluding fish stocks and markets, $P = (P_{ep}, P_{fp}, P_{cp})$.

A given state (X, P) is an equilibrium of the system if it satisfies balance and complementarity equations as follows.

6.5.1 Equilibrium on intermediate nodes

On intermediate nodes, (1) either ingoing flow is greater than outgoing flow and the price is null or (2) ingoing flow equals outgoing flow and the price is different to zero. In other words, there exist a price only if the supply fit the demand.

$$\begin{aligned}
P_{ep} > 0 \quad &\rightarrow \quad \sum_a X_{ap,ep} = \sum_f X_{ep,fp} \\
P_{ep} = 0 \quad &\rightarrow \quad \sum_a X_{ap,ep} \geq \sum_f X_{ep,fp} \\
P_{fp} > 0 \quad &\rightarrow \quad \sum_e X_{ep,fp} + \sum_q X_{fq,fp} = \sum_q X_{fp,fq} + \sum_c X_{fp,cp} + L_{fp} \\
P_{fp} = 0 \quad &\rightarrow \quad \sum_e X_{ep,fp} + \sum_q X_{fq,fp} \geq \sum_q X_{fp,fq} + \sum_c X_{fp,cp} + L_{fp} \\
P_{cp} > 0 \quad &\rightarrow \quad \sum_f X_{fp,cp} + \sum_q X_{cq,cp} = \sum_q X_{cp,cq} + L_{cp} \\
P_{cp} = 0 \quad &\rightarrow \quad \sum_f X_{fp,cp} + \sum_q X_{cq,cp} \geq \sum_q X_{cp,cq} + L_{cp}
\end{aligned}$$

6.5.2 Equilibrium on links

We have to take account of constraints due to limited fishing capacities or a limited canning capacities. There exist a shadow price for fleets or canning production industries, which is non negative and positive only when fishing capacity is fully used, and such that (1) either prices at origin plus transportation cost plus a shadow cost is greater than observed price at destination and there is no flow, (2) or price at origin plus transportation costs plus shadow cost equals price at destination and there is then a flow.

Concerning links from fish stocks to fleets, we have the following constraint: $\sum_a X_{ap,ep}/(q_{ap,ep}S_{ae}) \leq V_{ep}$. There exists $\lambda_{ep} \geq 0$ such that:

$$\begin{aligned}
\lambda_{ep} > 0 \quad &\rightarrow \quad \sum_a X_{ap,ep}/(q_{ap,ep}S_{ae}) = V_{ep} \\
\lambda_{ep} = 0 \quad &\rightarrow \quad \sum_a X_{ap,ep}/(q_{ap,ep}S_{ae}) \leq V_{ep} \\
X_{ap,ep} > 0 \quad &\rightarrow \quad P_{ae} + C_{ap,ep} + \lambda_{ep} = P_{ep} \\
X_{ap,ep} = 0 \quad &\rightarrow \quad P_{ae} + C_{ap,ep} + \lambda_{ep} \geq P_{ep}
\end{aligned} \tag{6.5.1}$$

Concerning links from fresh or frozen industries to canning industries, we must have $\sum_f X_{fcp} \leq U_{cp}$. There exists $\lambda_{cp} \geq 0$ such that:

$$\begin{aligned}
\lambda_{cp} > 0 &\rightarrow \sum_f X_{fp,cp} = U_{cp} \\
\lambda_{cp} = 0 &\rightarrow \sum_f X_{fp,cp} \leq U_{cp} \\
X_{fp,cp} > 0 &\rightarrow P_{fc} + C_{fp,cp} + \lambda_{cp} = P_{cp} \\
X_{fp,cp} = 0 &\rightarrow P_{fc} + C_{fp,cp} + \lambda_{cp} \geq P_{cp}
\end{aligned} \tag{6.5.2}$$

Concerning other links, (1) either prices at origin plus transportation costs are greater than prices at destination and there is no flow, (2) or prices at origin plus transportation costs equal prices at destination and there is a flow.

$$\begin{aligned}
X_{fq,fp} > 0 &\rightarrow P_{fq} + C_{fq,fp} = P_{fp} \\
X_{fq,fp} = 0 &\rightarrow P_{fq} + C_{fq,fp} \geq P_{fp} \\
X_{cq,cp} > 0 &\rightarrow P_{cq} + C_{cq,cp} = P_{cp} \\
X_{cq,cp} = 0 &\rightarrow P_{cq} + C_{cq,cp} \geq P_{cp} \\
X_{ep,fp} > 0 &\rightarrow P_{ep} + C_{ep,fp} = P_{fp} \\
X_{ep,fp} = 0 &\rightarrow P_{ep} + C_{ep,fp} \geq P_{fp} \\
L_{fp} > 0 &\rightarrow P_{fp} + C_{fp} = R_{fp} \\
L_{fp} = 0 &\rightarrow P_{fp} + C_{fp} \geq R_{fp} \\
L_{cp} > 0 &\rightarrow P_{cp} + C_{cp} = R_{cp} \\
L_{cp} = 0 &\rightarrow P_{cp} + C_{cp} \geq R_{cp}
\end{aligned} \tag{6.5.3}$$

To find the equilibrium state at each time step of the simulation, we have to solve an affine variational inequality. The following sections show how this kind of equilibrium is related to the variational inequality approach and how it may be computed.

6.5.3 Expression of constraints in the case of the global tuna commodity chain

Recall constraints

- $\sum_a X_{ae,ep}/(q_{ae,ep}S_{ae}) \leq V_{ep}$; (N_{ep} constraints)
- $\sum_f Xfp, cp \leq U_{cp}$ (N_{cp} constraints)

With $Z = ((X_l),(P_n)) = (((X_{ae,ep}),(X_{ep,fp}),(Xfp,cp),(X_{fpq}),(X_{cpq}),(L_{fp}),(L_{cp})),(P_n))$, we get :$A.Z \geq B$ where components of B are null except:

- $B_k = -V_{ep}$ for $k = 1, N_{ep}$, k corresponding to (e,p)
- $B_{N_{ep}+k} = -U_{cp}$ for $k = 1, N_{cp}$, k corresponding to $= (c,p)$

and components of A are null except:

- $A_{k,(aep)} = -1/(q_{ae,ep}S_{ae})$ for $k = 1, N_{ep}$, $k = (e,p)$
- $A_{N_{ep}+k,(fcp)} = -1$ for $k = 1, N_{cp}$

We have also to consider constraints expressing positivity of all components of Z.

6.5.4 Expression of matrices in the case of the global tuna commodity chain

We have several kinds of nodes: $N = \{N_{ae}, N_{ep}, N_{fp}, N_{cp}, M_{fp}, M_{cp}\}$. In which we distinguish producers: $P = \{N_{ae}\}$, transformers $G = \{N_{ep}, N_{fp}, N_{cp}\}$, wholesalers : $D = \{M_{fp}, M_{cp}\}$. We have several kinds of links : $L_{ae,ep} = \{(aep)\}$ concerns catches, $L_{ep,fp} = \{(efp)\}$ concerns affectation of a species to a fresh or frozen commodity, $Lfp, cp = \{(fcp)\}$ concerns production of a can commodity from a fresh or frozen commodity, $L_{fpq} = \{(fpq)\}$ concerns trade of a fresh or frozen commodity, $L_{cpq} = \{(cpq)\}$ concerns trade of a canned commodity, $L_{fp} = \{(fp)\}$ concerns consumption of a canned commodity, $L_{cp} = \{(cp)\}$ concerns consumption of a canned commodity.

We have to express:

$$M = \begin{pmatrix} M_{LL} & M_{LN} & M_{LQ} \\ -^T M_{LN} & 0 & 0 \\ -^T M_{LQ} & 0 & 0 \end{pmatrix} \quad , \quad N = \begin{pmatrix} N_L \\ 0 \\ N_Q \end{pmatrix}$$

Putting together previous definitions, we get:

- N_L : $N_{aep} = -P_{ae} - C_{aep}$, $N_l = -C_l$ for $l \notin L_{AEP}$ except $N_{fp} = -C_{fp} + a_{fp}$ and $N_{cp} = -C_{cp} + a_{cp}$
- N_Q : $N_{ep} = V_{ep}$, $N_{cp} = U_{cp}$.
- M_{LL} : $M_{ll'} = 0$ except $M_{(fp),(fp)} = b_{fp}$, $M_{(cp),(cp)} = b_{cp}$,
- M_{LN} : $M_{ln} = \delta^o_{nl} - \delta^d_{nl}$; thus $M_{ln} = 0$ except
  - $M_{(aep),(ep)} = -1$,
  - $M_{(efp),(fp)} = M_{(fcp),(cp)} = M_{(fpq),(fq)} = M_{(cpq),(cq)} = -1$,
  - $M_{(efp),(ef)} = M_{(fcp),(fc)} = M_{(fpq),(fp)} = M_{(cpq),(cp)} = 1$
  - $M_{(fp),(fp)} = M_{(cp),(cp)} = 1$
- M_{LQ} : $M_{lq} = \delta^d_{ql} f_{ql}$, thus $M_{lq} = 0$ except
  - $M_{(aep),(ep)} = 1/(q^p_{ae} S_{ae})$
  - $M_{(fcp),(cp)} = 1$

6.6 The network dynamics

Once the equilibrium has been computed, the values of flows on all links: $(X_{ap,ep}, X_{ep,fp}, X_{fp,cp}, X_{fp,fq}, X_{cp,cq}, L_{fp}, L_{cp})$ and those of prices on intermediate nodes (shadow prices): (P_{ep}, P_{fp}, P_{cp}) are all known. Then, they will serve to compute other variables of the system according to simple mathematical relationships.

Stocks evolve according to a production function. The functional relationship:

$$S_{ae} \to S_{ae} + r_{ae} S_{ae}(1 - S_{ae}/K_{ae}) - \sum_p X_{aep} \tag{6.6.1}$$

Fleets and canning industries evolve according to an investment function related to their profit function. The profit I_{ep} for fleet is obtained by the difference between the total sales or revenue of fishing products and the fishing costs. It is given by:

$$\begin{aligned} I_{ep} &= \text{total sales or revenue} - \text{ fishing costs} \\ &= \sum_f X_{efp} P_{fp} - \sum_a X_{aep} C_{aep} \end{aligned} \tag{6.6.2}$$

The profit of the canned production system I_{cp} is computed by the difference between canned revenue and the cost of purchase of fresh and frozen tuna plus the production cost of canned tuna:

$$\begin{aligned} I_{cp} &= \text{ sales } - (\text{ purchase of fresh } + \text{ production costs }) \\ &= \sum_q X_{cpq} P_{cp} - \sum_q X_{cqp} P_{cq} - \sum_f X_{fcp}(P_{fp} + C_{fcp}) \end{aligned} \tag{6.6.3}$$

Fishing capacity evolves according to an investment function. The following functional relationship is used with a depreciation rate η_{ep} and an investment rate σ_{ep}:

$$V_{ep} \to V_{ep} - \eta_{ep} V_{ep} + \sigma_{ep} I_{ep} \tag{6.6.4}$$

Cannery capacity evolves according to an investment function, a depreciation rate η_{cp}, and an investment rate σ_{cp} is used for the following functional relationship:

$$U_{cp} \to U_{cp} - \eta_{cp} U_{cp} + \sigma_{cp} I_{cp} \tag{6.6.5}$$

6.7 Summary of the modeling process

A synthetic view of the modeling process is given in box 6.7.

A whole picture of the model *State.* Variables defining a state of the system are:

- Flows $(X_{ap,ep}, X_{ep,fp}, X_{fp,cp}, X_{fp,fq}, X_{cp,cq}, L_{fp}, L_{cp})$
- Prices on all intermediate nodes $P = (P_{ep}, P_{fp}, P_{cp})$

Parameters. Parameters characterizing entities are:

- Fish stocks: S_{ae}, r_{ae}, K_{ae},
- Fleets: V_e^p, σ_e^p, η_e^p; Canneries: U_{cp}, σ_{cp}, η_{cp},
- Costs: $C_{ap,ep}$, $C_{ep,fp}$, $C_{fp,fq}$, $C_{f\to c}^p$, C_{fp}, $C_{cp,cq}$, C_{cp},
- Demand: a_{fp}, b_{fp}, a_{cp}, b_{cp}

Algorithm. At a given step:

- Update fishing costs: they depend on new values of stock abundances;
- Update some of the parameters according to scenario
- Compute resulting economic equilibrium using a variational inequality approach: compute matrices of the affine functional, solve the variational inequality, get resulting flows and prices;
- Using the values of flows given by the economic equilibrium, compute new values of fish stocks (formula 6.6.1), of fleets income (formula 6.6.2), of fishing capacity (formula 6.6.4), of canneries income (formula 6.6.3), of new canning capacity (formula 6.6.5).

6.8 Building scenarios

This section aims to explain how to built scenarios chosen by the model. The justification of scenarios chosen is already discussed in the introduction section. The principle of building scenarios lies in (1) associating the variation of a parameter to a scenario, (2) setting up before running the model, what will be observed concerning the dynamics of the system.

6.8.1 Defining parameters

Effects due to variations of parameters are here quantified. The main scenarios picturing effects imputed to changes in the petrol price, the productivity of industries, the demand of fresh and frozen tuna, the catchability of fishing industries, the current globalization system, and the implementation of marine protected areas to the Indian ocean high seas. Parameters corresponding to these scenarios are given in table 6.4.

Table 6.4: Parameters

Parameter	Symbol	Effect
Petrol price	π	$C_l \to \pi\ C_l$ for $l = (aep)$ (fishing costs)
Marine protected areas	θ	$C_l \to \theta C_l$ for $l = (aep)$ (fishing costs in several areas of Indian ocean)
Productivity changes	λ	$K_{ae} \to \lambda K_{ae}$ with K_{ae} carrying capacity
Globalization	γ	$C_l \to \gamma C_l$ for $l = fpq$, or $l = cpq$ (trading costs)
Demand changes for fresh or frozen tuna	δ	$a_{fp} \to \delta a_{fp}$
Catchability changes	κ	$q^p_{ae} \to \kappa q^p_{ae}$

6.8.2 Setting what to observe

The dynamics of the system is differently impacted according to the variable that acts. Changes in the network are observed following two types of pictures:

- variation of intensive variables that concerns all changes of costs on links and prices on nodes

- variation of extensive variables traducing variation of flows on links and quantities on nodes.

6.9 Conclusion

Following the main objectives of this work, this current chapter presented the model building processes. Starting with a recall of all entities characteristics that are the model basis, the bioeconomic model of the tuna commodity chain has been then implemented. The methodology followed the modeling principle applied to a dynamic network structure making linkage to diverse scenarios. The network equilibrium algebraically showed the way to reach an equilibrium state of the system focusing on the equilibrium of both intermediate nodes and links. The dynamics of the network itself made directory for the computation stage, once the equilibrium state of the system found. In this scenario-oriented model, scenarios built have been inserted to the model through parameters impacting the dynamics of the network. The model building is an intermediate stage before getting results. They greatly depend on data used for calibration. Both data types used and the detailed process of the model calibration are the main purposes of the next chapter.

Chapter 7

The calibration process of the bioeconomic model

Contents

7.1 Introduction

The bioeconomic model of the network structure of the global tuna chain has been previously formulated. For this scenario-oriented model, the main scenarios as well as the manner that they will be tested have been already described. We showed that each scenario is identified through a specific parameter. This present chapter aims to determine the values of both entities and parameters that characterize this model, that is the calibration process. Specifically for this simulation model, the calibration process remains an unavoidable stage. The fact of implementing an applied model, in other words, a data-oriented model, data are viewed as essential to estimate parameters. The process here contains two main stages: 1) the selection of entities and 2) the estimate of parameters from data. The first stage is already materialized in the two first chapters that dedicated to analyze and portray data that have been used to built the model. From these refined data, parameters are estimated in the present chapter that will serve to launch the simulation process further. In this current stage, biological parameters (stock level, carrying capacity, intrinsic growth rate) related to tuna catches and stocks characteristics are first estimated, and then, the assessment of technical parameters (production capacity, investment rate, capital depreciation rate) linked to the both fresh or frozen and prepared industries is made, and finally, economic parameters (costs, demand) that define the production and consumption processes are evaluated.

7.2 Initial datasets

In this section, we represent the result of previous estimates with an over lined symbol: $\overline{x}$ and the results of calibration or computation with a tilde symbol: $\widetilde{x}$. As previously seen, the estimates of values of all flows and trade prices, for the period

1993-2006 are provided. The mean values are then extracted. Computation of all other values will based on these initial datasets that are assembled below. We have thus estimates for:

- catches: $\overline{X_{ap,ep}}$,
- fishing efforts: $\overline{E_{ap,ep}}$,
- transformations of fish into a fresh-frozen commodity: $\overline{X_{ep,fp}}$,
- transformation of a fresh-frozen commodity into a can commodity: $\overline{X_{fp,cp}}$,
- trade of a fresh-frozen commodity: flows $\overline{X_{fp,fq}}$,
- trade of a can commodity: flows $\overline{X_{cp,cq}}$,
- import and export prices of fresh-frozen commodity: $\overline{IP_{fp}}$, and $\overline{EP_{fp}}$,
- import and export prices of can commodity $\overline{IP_{cp}}$, and $\overline{EP_{cp}}$,
- consumption of a fresh-frozen commodity: $\overline{L_{fp}}$,
- consumption of a can commodity: $\overline{L_{cp}}$.

We have also estimates of tuna stocks status from the website www.atuna.com. For each stock (a, e) we have an estimate of the healthiness of the stock $\overline{h_{ae}}$. It is supposed to be represented by the fraction S_{ae}/K_{ae}. More explanation is given further.

7.3 Calibration of nodes

For all nodes that define the network, their price should be found. The calibration of nodes show how these prices will be computed or estimated. This process regards all intermediary nodes like fleets and canning industries as well as adjacent nodes like stocks and trading systems. The price of each type of nodes will be approximated in a different way.

7.3.1 Tuna stocks or population

First, we intend to estimate the value of the intrinsic growth rate r_{ae} also called the rebuilding stocks value. It depends here essentially on the lifespan v of species with $r_{ae} = 2/v$ (see ICCAT (2010)). For each species, we consider its maximum age of the lifespan. The computed value of r_{ae} by tuna species is given in the table 7.3.1. This table shows the coefficient of the rebuilding stocks for the five tuna species that

Species	v (year)	$\widetilde{r_{ae}}$
SKJ	3	0.67
YFT	7	0.29
BET	7	0.29
ALB	5	0.4
BFT	20	0.1

Table 7.1: Renewal rates of tuna stocks(species age based on www.atuna.com)

are studied. The longer is the lifespan the lower is this coefficient. In others words, the longer a species lives the more its stocks take time to rebuild. The bluefin tuna stocks are the longest to rebuild and the shortest is for the skipjack stocks.

Then, from catches data $X_{ap,ep}$ measured in metric tonnes we expect to estimate the stock level S_{ae} (tonnes) for each species per distribution areas as follows:

$$S_{ae}(t+1) \quad = \quad S_{ae}(t) + r_{ae}S_{ae}(t)(1 - S_{ae}(t)/K_{ae}) - \sum_p X_{ap,ep}(t)$$

Where, r_{ae} is the intrinsic growth rate of the biomass (/yr) and K_{ae} the environmental carrying capacity (tonnes). The fish (tuna) population biomass is denoted by S_{ae} well known as stock.

We assume that the stocks average for the last ten years tend to equilibrium. The biological equilibrium assumption implies that tuna catches is equal to the stock renewal. This can be traduced by the following equations:

$$\begin{aligned} S_{ae}(t+1) &= S_{ae}(t) \\ \sum_p X_{ap,ep} &= r_{ae}S_{ae}(1 - S_{ae}/K_{ae}) \end{aligned}$$

The catch expression shows here the effect of fishing on population dynamics from Schaefer (1954) based on the logistic population model and applied it to the management of the tropical tuna fisheries and other fisheries. The level of exploitation of stocks is given by the ratio S_{ae}/K_{ae} (stock/carrying capacity). The more the stocks are exploited the lower is this ratio. For an endangered stock this ratio tends to zero and for a virgin stock it tends to 1. We assume that stocks are overexploited, fully exploited, moderately exploited, and under exploited when the fraction S_{ae}/K_{ae} gets the value 0.2, 0.35, 0.5 and 0.8, respectively. Information about the ratio S_{ae}/K_{ae} by area and tuna species are inspired to www.atuna.com. This ratio is detailed by species and by FAO area in the figure 7.1.

Figure 7.1: The level of exploitation of tuna stocks by FAO area (from http://www.atuna.com/)

The figure 7.1 shows that only skipjack tuna and albacore stocks are moderately exploited in some parts of the ocean. All the three other tuna stocks are either over fished (bluefin tuna, for example) or fully exploited (bigeye tuna, for example). The yellowfin tuna stocks are overfished in both western Indian and the Pacific (eastern central and south east) ocean and fully exploited in the rest of the oceans. We have to note that none of tuna stocks for the species studied here is underexploited. More details on parameters values of tuna stocks studied are given in the appendix in the section A.2.

Finally, the stock value may be estimated as follows:

$$\widetilde{S_{ae}} = \sum_p \overline{X_{ap,ep}} / (\widetilde{r_{ae}}(1 - \overline{h_{ae}})) \tag{7.3.1}$$

We have:

$$\sum_p \overline{X_{ap,ep}} = q_{ep} \widetilde{S_{ae}} \sum_p \overline{E_{ap,ep}} \tag{7.3.2}$$

Thus we may assume that:

$$\widetilde{q_{ep}} = \sum_p \overline{X_{ap,ep}} / (\widetilde{S_{ae}} \sum_p \overline{E_{ap,ep}}) \tag{7.3.3}$$

7.3.2 Fleets and canning plants

The fishing industries supply fresh and frozen tuna. Their production process is characterized by their production capacity V_{ep} (that is here the fishing capacity), the fishing effort $E_{ap,ep}$, the capital depreciation rate η_{ep}, and the investment rate σ_{ep}. The nomimal fishing effort $E_{ap,ep}$ is here defined by the number of standardized vessel-gear units actively fishing at a given time (Clark, 1985, p. 38).

We assume that all fleets deploy their maximal fishing effort to catch fishes. But their total fishing effort used is considered as fraction of their fishing capacity V_{ep}.

The fishing capacity is then assumed to be $\widetilde{V_{ep}} = 1.5 \sum_a \overline{E_{ap,ep}}$. Life of a boat is supposed about 10 years. The capital depreciation rate is $\widetilde{\eta_{ep}} = 0.10$. The half of profit is supposed to be reinvested. The reinvestment rate is estimated to $\widetilde{\sigma_{ep}} = 0.5$.

For *canned or prepared plants*, the production $X_{fp,cp}$ is considered as a fraction of the fresh or frozen production. The total prepared production is assumed to be a fraction of the prepared production capacity U_{cp}. Then, the cannned capacity is $\widetilde{U_{cp}} = 1.5 \sum_f \overline{X_{fp,cp}}$. The life of a factory is about 10 years. The capital depreciation rate is then $\widetilde{\eta_{cp}} = 0.10$. The half of income reinvested is $\widetilde{\sigma_{cp}} = 0.5$.

7.3.3 Commodities trade price

The trade price nodes qualifies the exchange flows inside the network structure. (1) The fresh and frozen trade price $\widetilde{P_{fp}}$ or $\widetilde{P_{fq}}$ is supposed to be the mean price of imports and exports for FF commodities. (2) The canned trade price $\widetilde{P_{cp}}$ or $\widetilde{P_{cq}}$ is computed as the mean price of imports and exports for canned commodities.

7.4 Calibration of links

This section explains the calibration process specifically for links. It also discusses the ultimate stage for the calibration process of producer nodes like fleets and stocks. Because estimating the value for these nodes requires to know first the value of links that hold them. The properly links calibration is first shown and the specific cases are then described.

7.4.1 Fishing

The fishing cost imputed to catches of one ton of tuna is qualified by the unit cost of fishing. The cost $C_{ap,ep}$ has one component related to effort $CE_{ap,ep}$ and one another attributed to catches $CY_{ap,ep}$. We have $C_{ap,ep} = CE_{ap,ep} + CY_{ap,ep}$. The value of $CE_{ap,ep}$ is inversely proportional to fish abundance S_{ae}. We have the usual relationship: $X_{ap,ep} = E_{ap,ep}S_{ae}q_{ep}$. Indeed, we express total costs as:

$$T_{ap,ep} = CY_{ap,ep}X_{ap,ep} + CE_{ap,ep}E_{ap,ep} \tag{7.4.1}$$

Then, the unit cost is so obtained:

$$\begin{aligned} C_{ap,ep} &= T_{ap,ep}/X_{ap,ep} \\ &= CY_{ap,ep} + CE_{ap,ep}E_{ap,ep}/(X_{ap,ep}) \\ &= CY_{ap,ep} + CE_{ap,ep}/(q_{ep}S_{ae}) \end{aligned} \tag{7.4.2}$$

7.4.2 Processing

The processing cost of a tuna species caught to a fresh-frozen commodity becomes null $\widetilde{C_{ep,fp}} = 0$ assuming the species price P_{ep} is the same as the FF commodities price P_{fp} from the fifth equation of the system 6.5.3.

The canned processing cost of a fresh-frozen to a canned commodity may be estimated from the third equation of the system 6.5.2 giving $\widetilde{C_{fp,cp}} = \widetilde{P_{cp}} - 2\widetilde{P_{fp}}$. To get this, the processing price of FF to canned commodities is assumed to be the double of the FF commodities price $P_{fp,cp} = 2P_{fp}$.

7.4.3 Trading

The trading cost is the cost imputed to the commodity exchange between countries p and q. For a fresh-frozen commodity, this cost is written $\widetilde{C_{fp,fq}} = max(0, \widetilde{P_{fq}} - \widetilde{P_{fp}})$ from the first equation of the system 6.5.3. For a canned commodity, it is estimated from the third equation of the system 6.5.3 resulting in $\widetilde{C_{cp,cq}} = max(0, \widetilde{P_{cq}} - \widetilde{P_{cp}})$

7.4.4 Selling

The selling cost is the cost attributed to the sale process of commodity. For a fresh-frozen commodity it is so assumed $\widetilde{C_{fp}} = 0$. From the seventh equation of the system 6.5.3, the selling price is deduced the same as the production price of the commodity $\widetilde{R_{fp}} = \widetilde{P_{fp}}$. The selling cost of a canned commodity is estimated from the ninth equation of the system 6.5.3. We make the assumption about the cost of the sale flows as $\widetilde{C_{cp}} = 0$. The selling price for canned commodities is so obtained: $\widetilde{R_{cp}} = \widetilde{P_{cp}}$.

7.5 Calibration of other nodes

7.5.1 Fleets

As, $\widetilde{C_{ep,fp}} = 0$, merging the first and the fifth equations of the systems 6.5.1 and 6.5.3, respectively, we must have:

$$\sum_a \overline{X_{ap,ep}}\,\widetilde{P_{ep}} \quad = \quad \sum_f \overline{X_{ep,fp}}\,\widetilde{P_{fp}} \tag{7.5.1}$$

We put:

$$\widetilde{P_{ep}} \quad = \quad \sum_f \overline{X_{ep,fp}}\,\widetilde{P_{fp}} / \sum_a \overline{X_{ap,ep}} \tag{7.5.2}$$

7.5.2 Fishing

Access to fishing resources is considered as free, i.e., fishing prices are assumed to be zero $\widetilde{P_{ae}} = 0$. Exception is made through scenario in which MPAs are implemented reducing access to resources with the existence of a fishing price or access price.

- When $\widetilde{P_{ae}} = 0$, from the third equation of the system 6.5.1, we get $\widetilde{C_{ap,ep}} = \widetilde{P_{ep}}$. We put: $\widetilde{CY_{ap,ep}} = \widetilde{CE_{ap,ep}} = (1/2)\widetilde{P_{ep}}$.

- With the MPAs implementation $\widetilde{P_{ae}} \neq 0$ and the third equation of the system 6.5.1 is integrally considered.

7.6 Beyond the calibration of links for the demand commodities

Parameters defining the demand curves of both FF and canned commodities are so estimated:

- FF demand parameters[1]: $\widetilde{a_{fp}} = 2\widetilde{P_{fp}}$, $\widetilde{b_{fp}} = \widetilde{P_{fp}}/\widetilde{L_{fp}}$.

- Canned demand parameters: $\widetilde{a_{cp}} = 2\widetilde{P_{cp}}$, $\widetilde{b_{cp}} = \widetilde{P_{cp}}/\widetilde{L_{cp}}$.

For the both types of commodities (fresh or frozen and prepared), their quantity sold on the market are known through data. From these data, the demand function could be established. The market concept here is defined through a country that sells a specific commodity. The commodity includes a tuna species and a type of transformation, i.e., fresh or frozen f and canned or prepared c. All markets are here defined as the function of inverse demand with the price P and the quantity L.

The quantity supplied or the total sale L is equal to the final consumption. The price P is the sale price on each market. The quantity L is known through data, that is the average consumption in volume during 10 years (1993-2006). The price P is taken as the weighted average price by the import and export quantity. Let P_I: the import price, P_X: the export price, I: the import in volume, and X: the export in volume. They are all known for each market on the same period. The price P is found as follows:

$$P = \frac{P_I * I + P_X * X}{I + X} \tag{7.6.1}$$

[1]From here P_{fp} and R_{fp} are interchangeably used, the same for canned commodities. The production price is assumed to be the same than the selling price

Once P is known, the demand inverse function on each market defined by the price P could be used to estimate the parameters a and b on these markets. Two strong assumptions are made to achieve this result.

1. The price P must be reached the average observed.

2. The coefficient of flexibility must be equal to -1: $\varepsilon = -1$

The coefficient of *price flexibility* of demand ε traduces the rapport between the percentage change in price and the percentage change in quantity demanded. It is the inverse of the coefficient of *price elasticity* of demand. The flexibility could be so written:

$$\frac{dP}{P} \div \frac{dL}{L} = \varepsilon$$

The unit elasticity or the unit flexibility $\varepsilon = |-1|$ means that the percentage change in quantity demanded is equal to the percentage change in price.

From the second assumption we could easily find a and b as follows:

$$\begin{aligned} \frac{dP}{P} \div \frac{dL}{L} &= -1 \\ P &= a - b * L \\ dP/P &= -b/P \\ dL/L &= 1/L \\ -b/P &= -1/L \\ b &= P/L \\ a &= 2 * P \end{aligned} \tag{7.6.2}$$

The value of parameters a and b are given in appendix A in its section A.3 for all fresh or frozen and prepared markets. The demand curves corresponding to values of these parameters are also portrayed.

7.7 Calibration: summary tables

7.7.1 The values of links

Values or flows of links are summarized in the table 7.2. They are obtained from data processed in the network analysis. This table only summarizes components and notation of all links within the network.

Table 7.2: Data concerning flows of links in the network

Quantity	Notation
Catches	$X_{ap,ep}$
Efforts	$E_{ap,ep}$
Transformation of fish into a FF commodity	$X_{ep,fp}$
Transformation of a FF into a CAN commodity	$X_{fp,cp}$
Trade of a FF commodity: flows	$X_{fp,fq}$
Trade of a CAN commodity: flows	Xcp, cq
Import and export of a FF commodity: import and export prices	IP_{fp} , EP_{fp}
Import and export of a CAN commodity: import and export prices	IP_{cp}, EP_{cp}
Consumption of a FF commodity	L_{fp}
Consumption of a CAN commodity	L_{cp}

7.7.2 Costs of links

The costs of links calculation that is also an objective of this present chapter are already estimated and assembled here in table 7.3. We know that all links are characterized by a cost level. Here are all cost attributed to links of the network and the manner they are computed.

Table 7.3: Constants concerning links

Parameter	Notation	Computation
Fishing costs	$C_{ap,ep}$	P_{ep}
Fishing costs (yield)	$CY_{ap,ep}$	$CY_{ap,ep} = (1/2)C_{ap,ep}$
Fishing costs (effort)	$CE_{ap,ep}$	$CE_{ap,ep} = (1/2)C_{ap,ep}q_{ep}S_{ae}$
Allocation costs	C^p_{ef}	0
Canning costs	$C_{fp,cp}$	$C^p_{fc} = P_{cp} - 2P_{fp}$
Trading costs of a FF com.	C^{pq}_f	$max(0, P_{fq} - P_{fp})$
Trading costs of a CAN com.	C^{pq}_c	$max(0, P_{cq} - P_{cp})$
Selling costs of a FF com.	C^p_f	0
Selling costs of a CC com.	C^p_c	0

7.7.3 Characteristics and values of nodes

The characteristics of nodes including prices and parameters are summarized in the table 7.4. They are all computed or estimated from the initial dataset as seen in the calibration section.

Table 7.4: Computation concerning nodes

Quantity	Notation	Computation
Catchability	q_{ep}	the healthiness of stocks $h_{ae} = S_{ae}/K_{ae}$ and $q_{ep} = r_{ae}(1 - h_{ae})/E_{ae}$
Stock	S_{ae}	$S_{ae} = X_{ae}/(q_{ep}E_{ae})$, Renewal rate $r_{ae} \simeq 2/v$
Carrying capacity	K_{ae}	$K_{ae} = S_{ae}/h_{ae}$
Fishing price or access	P_{ae}	$P_{ae} = 0$ or $P_{ae} \neq 0$
Fishing capacity	V_{ep}	The maximum value of effort during the last 10 years
Depreciation rate for a fleet	η_{ep}	Life of a boat is supposed about 10 years; $\eta_{ep} = 0.10$
Investment rate of a cannery	σ_{ep}	Half of income reinvested; $\eta_c^p = 0.5$
Canning capacity	U_c^p	The maximum value of can production during the 10 last years
Depreciation rate for a cannery	η_c^p	Life of a boat: 10 years; $\eta_c^p = 0.10$
Investment rate of a cannery	σ_c^p	Half of income reinvested; $\eta_c^p = 0.5$
Price of a FF commodity	P_{fp}	mean of the FF imports and exports prices
Price of a CAN commodity	P_{cp}	mean of the canned imports and exports prices
Demand parameters for a FF commodity	a_{fp}, b_{fp}	$a_{fp} = 2P_{fp}$, $b_{fp} = P_{fp}/L_{fp}$
Demand parameters for a CAN commodity	a_{cp}, b_{cp}	$a_{cp} = 2P_{cp}$, $b_{cp} = P_{cp}/L_{cp}$

7.8 Conclusion

In this current chapter values of parameters have been estimated. The detailed calibration process of the global model has been highlighted. From data that have been already analyzed, some parameters assembling into nodes or links are computed. Prices are estimated for nodes and costs for links. The flows level already known through data simplifies the complexity of the equations systems including many unknown variables. For reduction, a lot of assumptions are also made. These simplifying assumptions are sometimes realistic. And the most part of parameters in the model are estimated from real data. These points, as in all applied models, strengthen the model reliability by contrast to theoretical models. However, the choices made will obviously impact results reflecting all these specific cases found in assumptions. All the previous steps are only shown the modeling process in its theoretical or mathematical ways. While the model results will be obtained from simulation process. This last process is numerically implemented. That is the main purpose of the following chapter in which the model is launching in order to get the simulation outputs.

Chapter 8

The model implementation

Contents

8.1 Introduction

The two previous chapters have got focus on the model description and the way to calibrate the model parameters. These chapters did not specify how could perform the model when running. This point is tackled in this current chapter. It specifically aims to explain the numerical implementation of the model. The main stages describing that process is detailed as follows:

- From the network data files set up initial values of parameters
- Matrix and vector building from the network data found in different files
- Changes in parameters values through several files
- Write numerically the problem calling different functions
- Solve the problem through an algorithm calling these functions and taking network data as input
- Run the algorithm to get the model out puts

These points explain the main steps followed to achieve the simulation results. However, they could be summarized in only two major stages: The matrix and vector building and the system equilibrium calculation for the dynamic programming. These two points will be highlighted throughout the following sections. More materials for the equilibrium computation and the software programming are provided in the appendix .

8.2 Matrix and vector building

On large size matrix and one vector will serve as input for the simulation process. The matrix M and the vector N are all the both built according to the formula described according to the theorem 6.4.3 in appendix. Their structure looks like:

$$M = \begin{pmatrix} M_{LL} & M_{LN} & M_{LQ} \\ M_{NL} & 0 & 0 \\ M_{QL} & 0 & 0 \end{pmatrix} \quad , \quad N = \begin{pmatrix} N_L \\ 0 \\ N_Q \end{pmatrix}$$

Where, L, N, and Q used as index, are respectively, the total number of links, transformer nodes (i.e., fleets, FF producers, and canned producers), and constrained transformers nodes (fleets and canned producers) existing in the network. The vector N is so computed:

- N_L: $N_{aep} = P_{ae} + C^p_{ae} + CE^p_{ae} * \frac{S_{ae}(t)}{S_{ae}(t+1)}$, $N_l = C_l$ for $l \notin L_{AEP}$ except $N_{fp} = C^p_f - a^p_f$ and $N_{cp} = C^p_c - a^p_c/2$
- N_Q: $N_{ep} = V^p_e$ and $N_{cp} = U^p_c$

The matrix MM entries are obtained as follows:

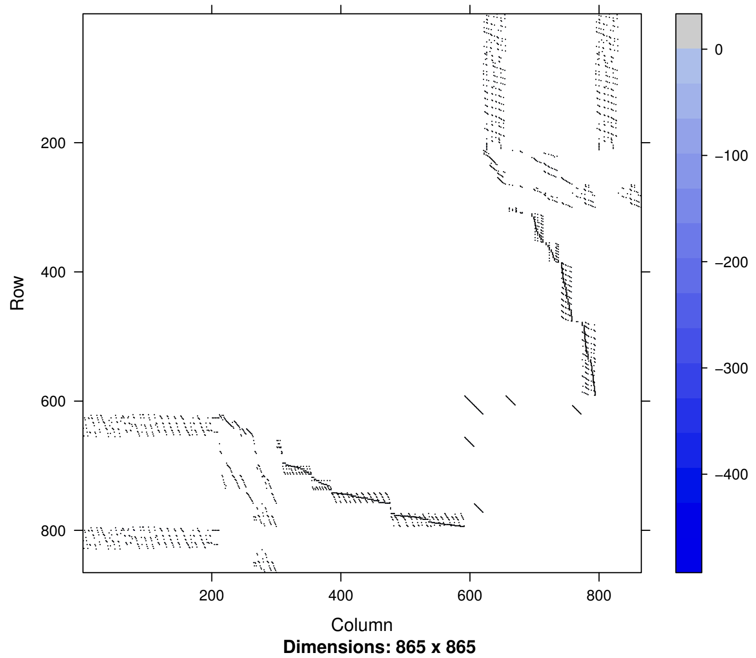
- M_{LL}: $M_{ll'} = 0$ except $M_{(fp),(fp)} = b_{fp}$ and $M_{(cp),(cp)} = b_{cp}/2$,
- M_{LN}: $M_{ln} = \delta^o_{nl} - \delta^d_{nl}$(destination-origin), thus $M_{ln} = 0$ except
  - $M_{(aep),(ep)} = 1$,
  - $M_{(efp),(fp)} = M_{(fcp),(cp)} = M_{(fpq),(fq)} = M_{(cpq),(cq)} = 1$,
  - $M_{(efp),(ef)} = M_{(fcp),(fc)} = M_{(fpq),(fp)} = M_{(cpq),(cp)} = -1$

- $M_{(fp),(fp)} = M_{(cp),(cp)} = -1$

- $M_{NL} = -M_{LN}$
- M_{LQ}: $M_{lq} = 0$ except $M_{(aep),(ep)} = 1$ and $M_{(fcp),(cp)} = 1$
- M_{QL}: $M_{lq} = 0$ except $M_{(ep),(aep)} = -1/(q^p_{ae} S_{ae})$ and $M_{(cp),(fcp)} = -1$

The matrix M is a large matrix with 865 lines and columns and belongs to the sparse matrix category in which the most part of entries are zero. The dimension of this symmetric and square matrix is obtained considering the total sum of all links (620), transformers (174), and constrained transformers (71) inside the network. The vector N with the same length as M contains 865 elements but the most of them are non zero. The figure8.1 shows the sparsity of the matrix plotting all its non zero values. All zeros are represented in the blank area of this graph.

The matrix M and the vector N are considered as main arguments for some functions featuring the algorithm that aims to found the system equilibrium. This algorithm is detailed in the following section.



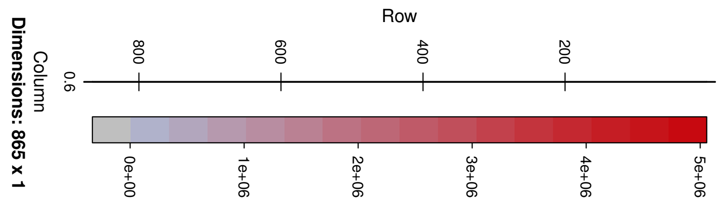


Figure 8.1: The sparsity of the matrix M (top) and the length of the vector N (down)

8.3 Dynamics

The model is identified as dynamic because the equilibrium change through time. All the process is detailed in the chapter related to the model formulation (chapter 6)). Talking here about the system dynamics allows only to show what is the next in the model numerical implementation process once the equilibrium state find. The vector solution X_s obtained from the equilibrium state provides all necessary tools for the future computation. It includes values of all flows and shadow prices. These values will be very useful for the dynamics of the producer nodes as well as for their computation as explained below.

- The dynamics of stocks is computed according to the equation 6.6.1 from the new values of catches provided by the solution.
- The fleets dynamics is first traduced by the equation 6.6.2 linking their profit function to both the production flows of tuna FF and the shadow prices. They are all the both given by the solution of the equilibrium state. And then, the equation 6.6.4 updating the fleets capacity values that depend on those of the fleets profit.
- The canning production dynamics follows the same way as the fleets dynamics. From the equation 6.6.3 the profit of the canning industries is obtained according to the new values of canned production flows and shadow prices provided by the equilibrium. The value of the canning capacity is deducted from the equation 6.6.5 including the canning industries profit.

8.4 Conclusion

This present chapter explains how the model could numerically work. The model implementation and running on the programming software R are also shown. The whole model in its applications is functional and accurate. The algorithm used could be easily applied to other programming software. Until then the model has been simply ran without consideration of diverse scenarios previously cited. The model dynamics programming itself provides results of the stationary state, i.e., without variations of parameters related to scenarios. This last process will be easily integrated into the running process by choosing one by one which scenario to test that is to say which parameter to modify. This issue will be more detailed by presenting results of each scenario separately as well as the variations of the corresponding parameter. This is the main purpose of the following chapter.

Part V

Results of scenarios tested from the model

CHAPTER 9

Model results of contrasted scenarios

Contents

9.1 Introduction

This current chapter aims to outline simulation results from the bioeconomic model developed in the three previous chapters. These results are expressed by the various scenarios tested. The way scenarios have been implemented into the model is previously explained. Remind that each scenario is related to a model parameter. Results of scenarios will be obtained by changing one by one each parameter and then run a simulation to get the model outputs. In this present chapter, simulation results from the model at the stationary state are first shown and for the need of this current work some specific scenarios have been tested. The scenarios tested by the model and their results are then summarized in the following sections: closure of all parts in the Indian Ocean to fishing, a rising of the fresh and frozen tuna demand, and a rising of the oil price. The model outputs from these scenarios will be detailed below and show how these changes will affect the model dynamics.

9.2 Results of scenarios

9.2.1 The steady state

In the steady state there is no significant changes from the beginning to the end of simulation. No parameter is changed while the model dynamics follows its way without perturbation and results are globally remained constant. The stationary state is also considered as the reference state for the scenarios tested. The figure 9.1 displays the model dynamics for all important entities defining the model with a monthly time step for 56 months. The stocks dynamics slightly moves throughout the simulation period. The same trend is followed for both Indian and non-Indian Ocean stocks and catches. Some fresh/frozen commodities components like trade and income shape a continuous sawtooth variations throughout the simulation period while some others like fishing capacity and consumption as well as all components related to canned commodities remains continuously constant.

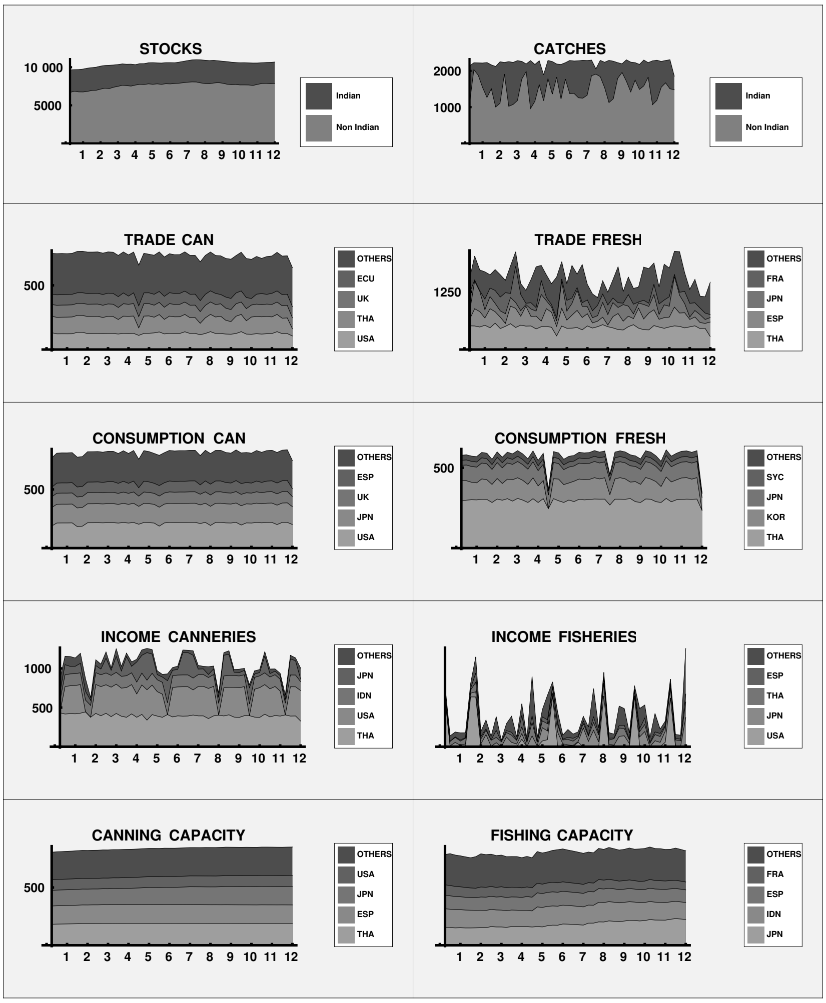


Figure 9.1: Steady state scenario

9.2.2 Indian Ocean closure

The first scenario tested is the closure of all parts in the Indian Ocean to fishing. The fishing cost in these areas are considered so high that all fleets have to move to other parts in the ocean. All the fishing effort from the IO is supposed to be redistributed elsewhere. The figure 9.2 displays important results from this scenario. These results could be so commented:

- At the beginning of the simulation, IO tuna stocks almost represent one third of the total tuna stock in the worldwide ocean. Throughout the simulation process, IO stocks are rising because catches are inexistent while in the open areas, the high concentration of fleets leads to outrageousness catches through time and tuna stocks quickly decrease and tend to collapse. At the end of simulation, IO stocks constitute some 95% the total tuna stocks.

- As exploited stocks decrease through time, tuna products (fresh/frozen and canned) exchanged between countries also decline through time. Fleets that mainly involve in the IO ocean areas like France disappear on the top fresh/frozen tuna trading countries. The FF trading values increase and peak some 2500 MT during the simulation before decreasing. Canned trading decrease more quickly than FF trading. At the end of simulation the former globally tends to zero and the latter remains very low.

- For the consumption of both commodities, there is no significant changes for the rank of top consuming countries by comparison to the consumption in the steady state. However, about the consumption level during the simulation period, for the both types of commodities, it shapes a decreasing trend until reach a very low level at the end of simulation. Specifically for the FF consumption, the closure of the IO to fishing reduces the FF consumption to 18 % (from 600 MT to 500, values at the beginning of the simulation).

- Income from tuna fisheries globally increases twice more than the one of the stationary state. It defines the same shape as in the latter at the beginning and then known a stable rising until a slightly decreasing at the end. The income from fishery grows because, tuna stocks are fully exploited, tuna species because scarce, and the tuna prices increase until tuna stocks. However, the total fishing capacity starts with a low level and then grows during the simulation to reach its maximum value at the end but representing only one quarter of the total fishing capacity in the reference state. Income from canning industries diminishes trough time while the canning capacity remains stable like in the stationary state as if the closure has had no direct effect on the canning production.

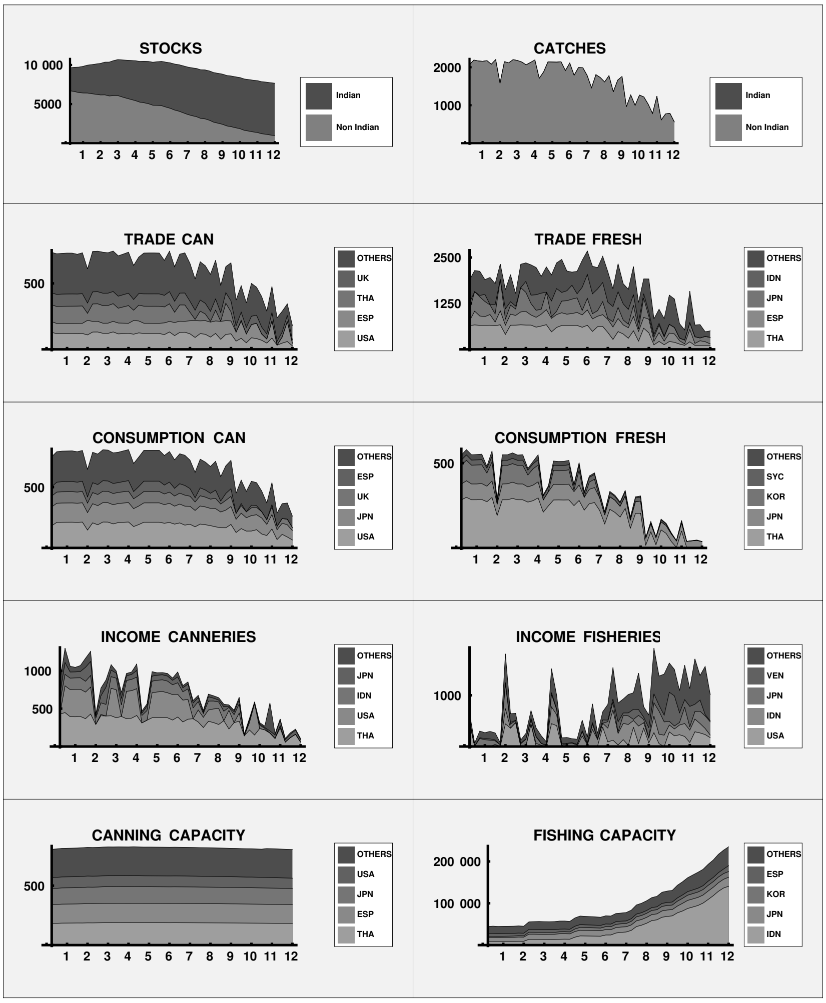


Figure 9.2: closure of all areas in the Indian Ocean to fishing

9.2.3 Increase in the tuna demand

The effect of an increasing demand on the FF tuna markets has been tested. The parameters related to the demand function have been modified in the following way: 10% increasing per year for the FF demand parameters a_f and b_f. This variation corresponds to some 1% increasing on a monthly time step and its consequences are displayed in the figure 9.3. This current scenario affects the model dynamics in the following ways:

- The first observation is that all stocks quickly decrease until a complete collapse before the end of simulation. Tuna stocks decrease until their breakdown because catches are exponentially rising (until a limit) for satisfying the increasing fresh demand. When the tuna stocks are fully exploited and tend to collapse, catches obviously decrease and remain very low at the end of simulation.

- An increasing of fresh tuna demand affects both the fresh/frozen and canned markets. The two industries start with an increasing trend, reach a peak and then decrease. The FF and the canned trades grow by some 25 % (at their maximum level) compared with their values at the beginning of simulation. The exchange flows for the both types of commodities are shared between the same trading countries as in the reference state but with a quite difference in the rank. The global consumption follows the same rising as the trades. The FF consumption reachs a peak with 40 % of increasing and the canned consumption with 30%. The FF consumption is more affected by a change occuring on the FF markets. It grows as well as decreases more quickly.

- The profit made from the fishery activities increases all the simulation period long. The one from the canned industries, grows and reach a peak by 8% increasing, and finally decreases. The FF income knows some 7% growth at the end and do not cease to raise. When the income grows industries needs to appropriate new technology by doing more effecient their production capacity. That is why both fishing and canning capacities are raising over the simulation period.

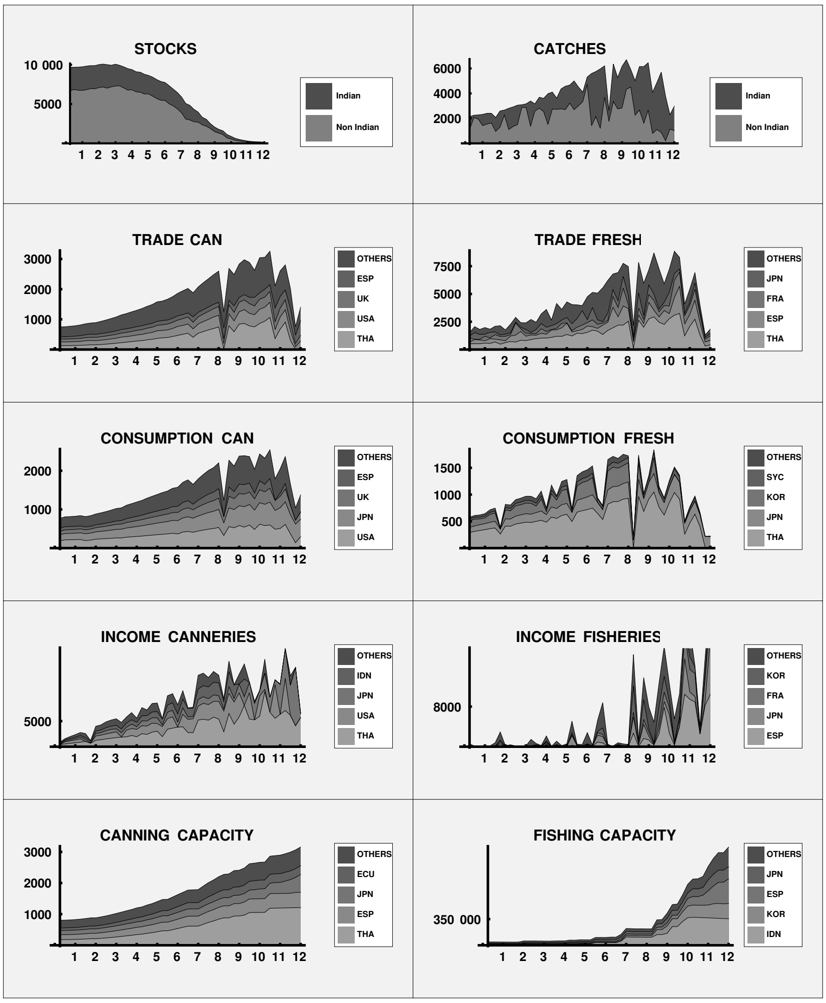


Figure 9.3: Increase in the tuna demand

9.2.4 Regular increase in the oil price

The scenario of the variation of the oil price is traduced by an increasing to 20% of both fishing and shipment costs. How this supplementary cost added to the system affects its dynamics is displayed in the figure 9.4 and explained as follows:

- The global stock remains constant and it knows a slight increase at the end of period. As the fishing cost rises, tuna catches tends to stabilize until a low decreasing at the end for all oceans.
- The variation of the oil price lowly affect the global trade and consumption. All these components are subjected to diminish over time except the FF trade that trends to grow.
- With the global increasing shape of consumption for both industries, the income from FF industries lowly increases indeed remains stable.The economic activities globally slows down.

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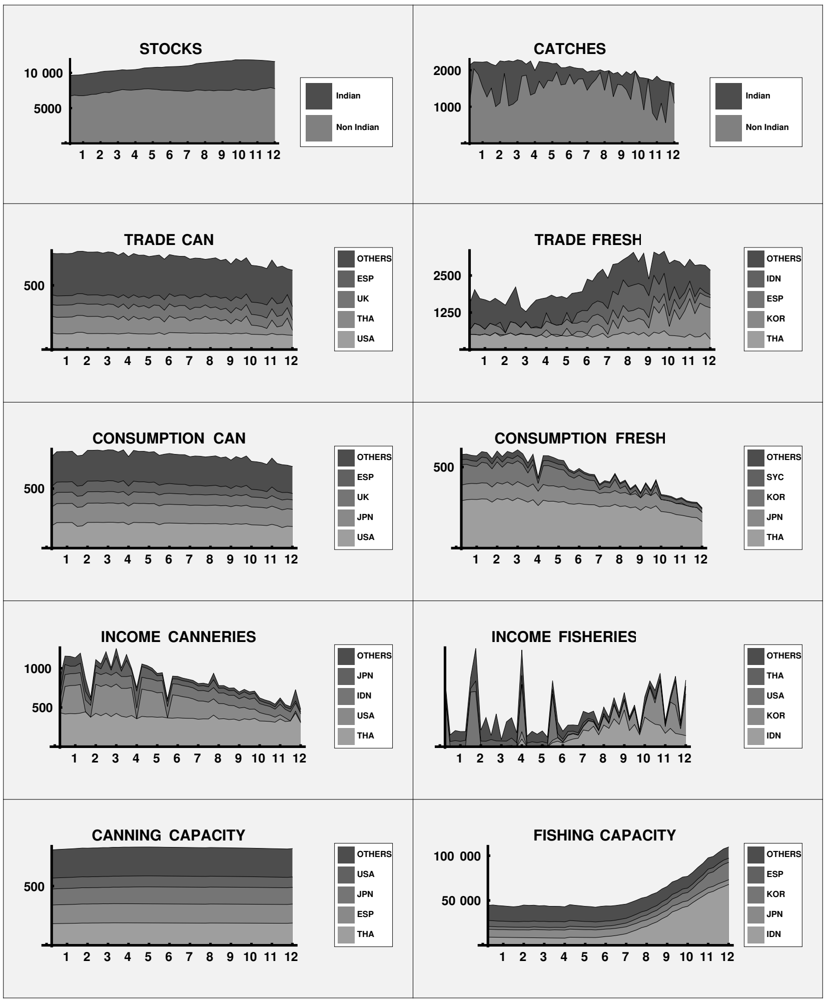

Figure 9.4: Regular rises of the oil price

9.3 Conclusion

All the scenarios above are presented in a contrasted way. They are only defined by a strong hypothesis in order to follow how the model dynamics evolves and how its could undergo variations. By doing so, all scenarios are independently considered and the model is not subjected to other exterior perturbations, i.e., it works in a deterministic environment. When the IO stocks are chosen to collapse all components of the model dynamics follow the same shape (except the fishing income and capacity) as the global stocks i.e., decrease. The fishing industries continues to increase their activities because the FF price being high makes profitable the fishing activities over a long period of time. An increase in the FF demand affects the entire system. It leads tuna stocks to collapse while encouraging the economic activities for both industries by increasing the trades, consumption, income, and production capacity until the limit. However, by increasing the oil price, the tuna stocks are durably exploited as if a global marine protected areas has been implemented. This situation highly penalize the both industries that become unprofitable because subjected to an excessive cost. Although these scenarios have been tested in a perfect world but they confirm some classic results. The following chapter will try to fill this gap by testing scenarios in a more realistic environment.

Chapter 10

Comparing strategies for offshore Marine Protected Areas

Contents

10.1 Introduction

Tuna fisheries are known to face great challenges including: the fishing capacity control, the profitability improvement, the management issue, the limitation of impacts on high seas biodiversity, ect. Tuna fisheries are also involved in a complex system where the exploitation of tuna stocks is done within and beyond exclusive economic zones (EEZ) by coastal states as well as distant water fishing nations. The highly migratory characteristic of tuna species that overlap in high seas areas intensifies the traditional fisheries management issue. The purpose of the current chapter is to discuss about the scenarios results regarding the implementation of MPAs in high seas zones.

Based on the bioeconomic model developed in chapter 6, we present simulation results for comparing strategies for offshore MPAs. Specifically, two main strategies will be compared:

- Closure of Indian Ocean high seas
- Closure of Atlantic Ocean high seas

For the two scenarios, we consider that tuna stocks are endangered before the closure. Concretely, we take 10% of the carrying capacity for the two oceans where tuna stocks have to be protected. We also make the hypothesis according which there exists an annual increasing rate of 5% for the FF demand. We keep the hypothesis for canned industries that invest twice quickly than the reference scenario. Under all these hypothesis, the model has been ran for each scenarios separately. Results obtained from simulation for each scenario will be outlined in the following sections.

10.2 Scenarios analysis

In this section results of scenarios tested for high seas MPAs are analyzed.

10.2.1 Closure of the Indian Ocean high seas

In this scenario high seas areas in the Indian Ocean are closed to fishery. The most part of the closure is located in the western part of the Indian Ocean. In the figure 10.1, the areas in light gray represent zones closed to fishing and other parts in the oceans in dark gray are all opened to fishing. Simulation results for high seas closure in the Indian Ocean are displayed in figure 10.2. Like the previous simulation results presented in chapter 9, the output from the model is given here showing how the system dynamics is affected by these changes. The key points for the simulation results when closing some high seas areas in the Indian Ocean are synthesized below:

- The global stock level (for all oceans) is decreased through time while both Indian and non Indian catches slightly increase at the end of the simulation.
- The global trade for canned industries is not directly affected by changes occurring. FF trade increases over time following the same shape with catches. Trading countries for canned industries keep their rank by comparison with the reference scenario excepted Spain that become the top trader followed

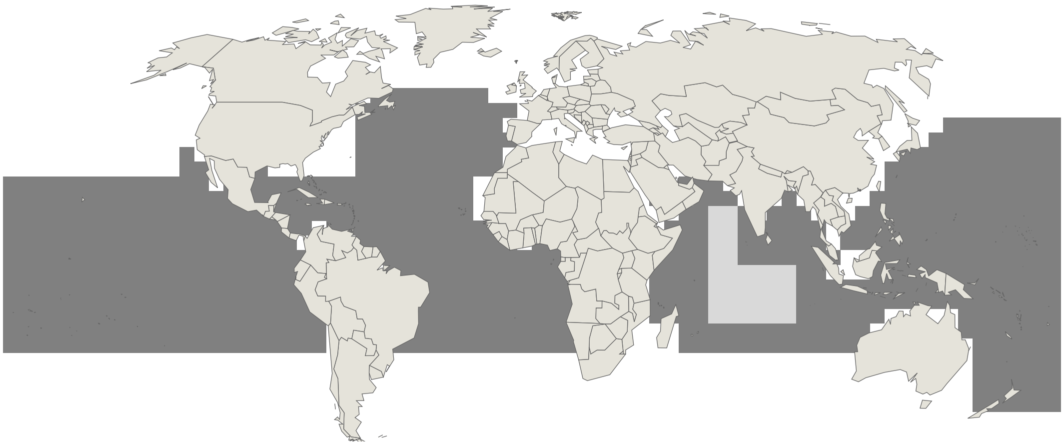

Figure 10.1: closure of the Indian Ocean High Seas

by England. For FF trading countries, France loses its first place because a major of part of its catches are concentrated in the areas closed (the western IO).

- The canning intake remains stable over time while those of FF increases. Although an increasing annual rate of FF demand has been maintained before simulation, the global FF consumption at the end of the simulation period has been doubled compared with the reference situation. Both FF and canned consuming countries keep their rank.

- Closure of high seas areas in IO indicates no significant effects on the profit level for canning industries as well as on their production capacity. Profit made from FF commodities increases all the period long. Some countries like Korea and Indonesia make a better profit than other top FF producer like Spain and Thailand. The fishing capacity grows through time and reaches its maximum level at the end of the simulation.

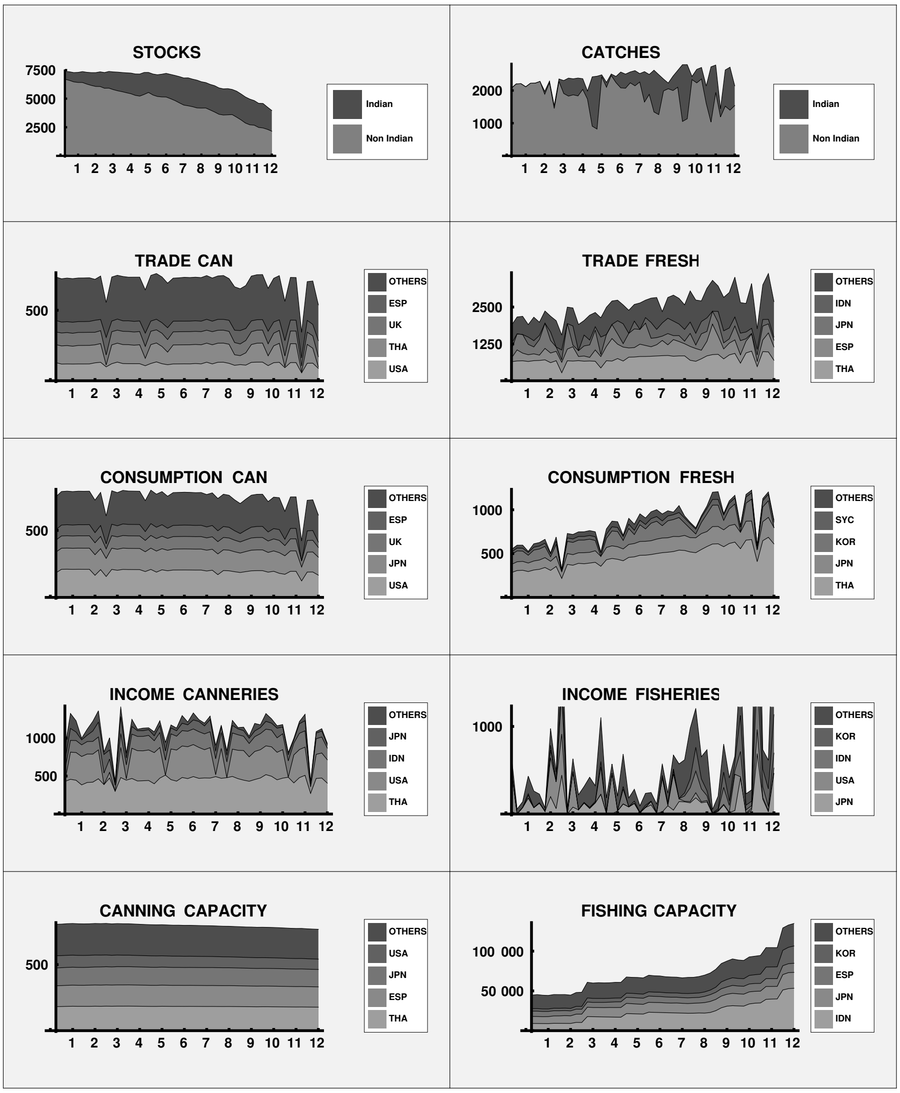

Figure 10.2: Scenario results of MPAs in Indian Ocean High Seas

10.2.2 Areas closure in the Atlantic Ocean

In the current scenario, we consider a major part, almost 80%, of the AO (north, central, and south) close to fishing, as shown in figure 10.3. Closed areas are in light gray and opened areas in dark gray. The most part closed is located in high seas. Testing MPAs in the AO is done with the same hypothesis made in the previous scenario for IO. The way the system dynamics is affected by these changes is displayed in figure 10.4 and then summarized in the following items.

- Global tuna stocks exploitation remains stable. Until the end of simulation,

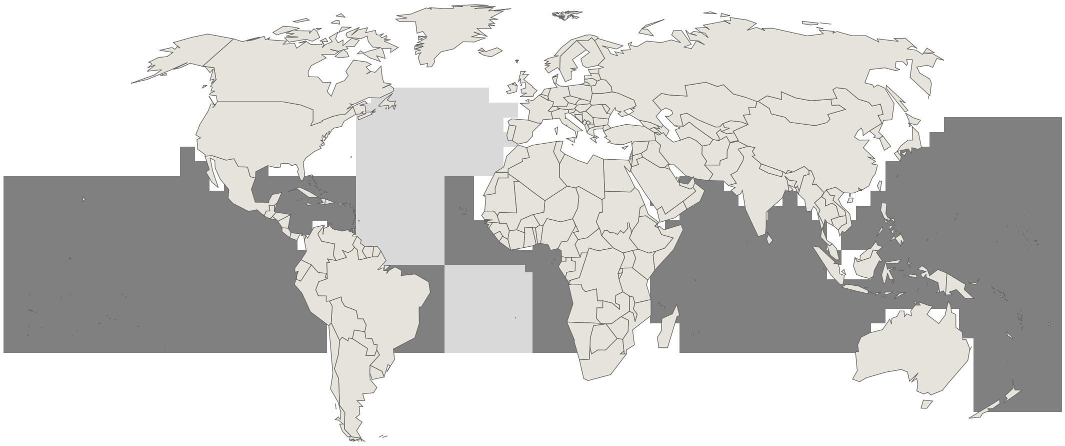

Figure 10.3: Areas closure in the Atlantic Ocean

the 10% of the carrying capacity from the reference state is kept. Tuna catches increase at the end of simulation. Although the tuna catches are increasing, stocks remain stable because the areas closed could provide enough spill over to fishery to counterbalance the take off from catches.

- Catches provides product for markets. As catches increase, the FF trade follows the same way. Compare with the reference state, the FF trade is almost doubled at the end of period. The top trading countries keep their rank with France the first trading country. For canned commodities, no significant changes have been observed.

- The canned consumption remains stable at the beginning of the simulation and then slightly decreases at the end. The FF consumption increases and triples at the end of simulation. The healthiness of tuna stocks leads to increase catches to feed this growing FF demand.

- Canning industries make profit from the closure of a great part of the AO areas. At the end of simulation profit from canned commodities roughly increases to 25% without improvement of the production capacity. The canning capacity remains stable. For fresh commodities, profit knows a slight increasing because the availability of tuna on the markets (increasing trade) that leads to a dropping prices. The fishing capacity has known an increasing.

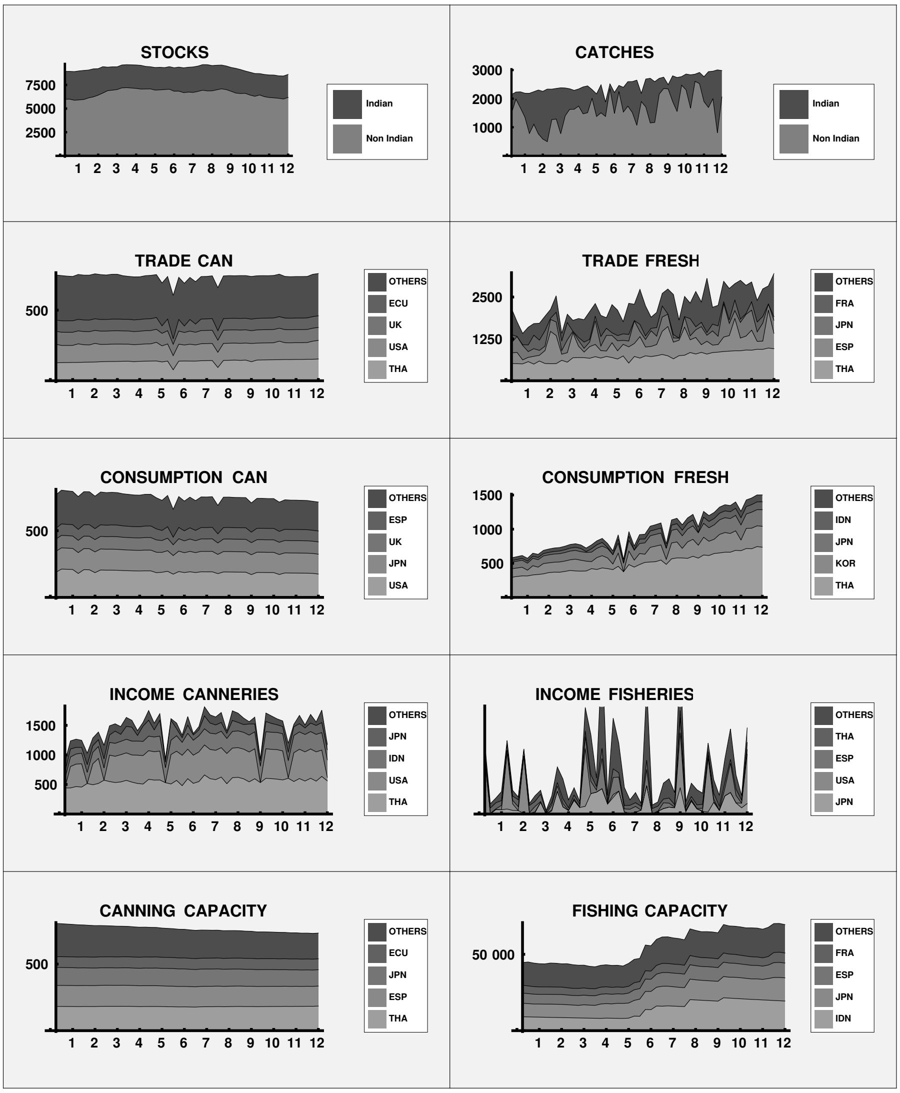

Figure 10.4: Scenario results of MPAs in Atlantic Ocean

10.3 Conclusion

The current chapter presented simulation results from two scenarios of MPAs: (1) closure of the IO high seas to fishing and (2) closure of a great part of the AO. The two scenarios have been tested under the same hypothesis with a growing FF tuna demand and endangered stocks in areas to protect before implementing MPAs. The first scenario shows, although a MPA is implemented in the IO, it is not enough to avoid collapse in the whole ocean stocks. In other words, the area protected can not counterbalance the take off. This scenario also shows no significant effect on the canning commodities network (trade, consumption, profit, and investment). The second one provides significant effects on the global network chain (FF and canned commodities). However, effects are more immediate and direct on the FF commodities. This scenario proves the MPAs efficiency in that they provide spillover to adjacent fisheries and repair a damaged ecosystem by recovering endangered stocks. Comparing these two scenarios with the MPAs scenario in chapter 9 in which all the IO is closed to fishing, results obviously differ. Closure of the whole IO can not prevent collapse of all two other oceans (AO and PO), despite of the IO stocks were not considered as endangered before MPAs. This last scenario was showed a complete decreasing trend through time for the entire network from catches until the final consumption.

Part VI

Discussion

General conclusion

This current work by analyzing the network structure of the tuna chain comes to present a model of the GTCC. From a large set of data, an applied model has been implemented. This scenario-oriented model shows the model response against some actual challenges that face the worldwide tuna chain. These scenarios are related to the increasing petrol price, the rising of the fresh demand, and the implementation of global MPAs. This last scenario, which constitutes the main objective of this current work, is tested in order to bring responses about the actual question posed on the efficiency of MPAs. This question is widely debated throughout this work with a hard literature support. The MPAs scenario results show that is both economically and biologically efficient to protect a large part of the ocean by increasing biomass in the protected areas and by increasing fishery rent in the open areas.

The different scenarios tested by the model provide coherent results. First of all, the model knows a steady state equilibrium throughout all the simulation period when no perturbation occurs in this system dynamics.

An increase in the FF demand is an economic success but an ecological disaster if we are confident in the model. An increasing demand is a realistic scenario knowing that the growth rate of the world population increases the more and more. We saw that the economic activities are successful but in long term when raw material (natural resources) will become scarcer that will be no longer the same.

By increasing the oil price, the system dynamics has been deeply changed. The worldwide stock is protected but both fishing and prepared industries become economically inefficient. The increasing petrol price as all measures that increase the fishing cost such as taxes, royalties etc., provide good results only for the conservation of fish stocks. These supplementary costs make dishearten the economic activities, impacting fishery profit, wages...As MPAs, these measures punish the present generation and maybe in favor of the future one.

A closure of all parts in the Indian Ocean affects the model dynamics in its wholeness. Pressures on tuna stocks in other parts of the ocean intensively accelerates until collapse. This situation highly affects the FF consumption while increasing the FF income. All the prepared chain is punished because raw material become too scarce. The hypothesis about the efficiency of MPAs is partially verified. The IO stocks are well protected but does not provide enough spillover for the period to recover stocks that are quickly depleted in the two other non protected oceans. The fishing industries are profitable only because prices are rising affecting the global consumption of tuna and tuna products. However, the current scenario does not take into account the pre-reserve conditions.

When the pre-reserve condition is considered, the results differ as seen in chapter 10. The key question is how large must be MPAs to compensate taken stocks. With MPAs other management tools are not considered while MPAs is revealed as a good complementary tool to avoid failure (Lauck et al., 1998). In all MPAs scenarios, results could be very different or maybe more satisfactory if in the two open oceans a simple management tool (TAC, fishing license, tax...) were enforced in order to strengthen the efficiency of MPAs also known as a complementary tool in fishery management. These last points raise here traduce the limitations of the current work excluding some questions about implementing MPAs. The MPAs scenarios described global phenomenon ignoring important effects such as adults or juveniles movement, mortality control, and fleet movements.

Remind that the main objectives of this Ph.D thesis were to (1) picture the structure of the GTCC in a network framework, (2) design a bio-economic dynamic model of the GTCC in which all components of the network are included, (3) test realistic scenarios considering the main stakes that face the worldwide tuna global chain. The great challenge with this work consisted in using large sets of data in order to create an applied model. That point was supposed to increase the model liability by contrast to a theoretical one.

We have partly realized this program. We have proven the possibility of a network representation of a global commodity chain in the network framework, with an unusually large number of components. We have presented only a small number of the pictures of the system provided by this kind of representation. Now the question is open concerning the pertinence of this representation for the building of consensus that is now necessary in the perspective of a global management (Islam, 2008). In the network framework, we have formulated and calibrated a dynamic model. We have illustrated its possibilities by implementing several scenarios, with a focus about offshore marine protected areas. This model in its present state cannot be said a realistic model. However, we think that our approach can be iterated, using these preliminary results for a better design of the network, new data representations, new scenarios, etc..

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Part VII

Appendices

Appendix A

Appendix

In this appendix, we give the values of the parameters that we have obtained after the calibration process described in chapter 7.

A.1 Main parameters

Parameters, to at least their order of magnitude, have been estimated according to tables A.1 and A.2

Parameter	Notation	Meaning and estimation
Catchability	S_{ae}	From Sardara : $\overline{q}_{ae} = a/b$, where $(Y/E) = a - bE$ is the regression line relating catches per unit of effort to effort.
Initial stock	S_{ae}	From Sardara : $\overline{S}_{ae} = \overline{Y}_{ae}/(q_{ae}\overline{F}_{ae})$
Carrying capacity	K_{ae}	From Sardara : $\overline{K}_{ae} = 2\overline{S}_{ae}$
Renewal rate	r_{ae}	From Sardara $\overline{r}_{ae} = 2\overline{Y}_{ae} = 2\overline{Y}_{ae}/\overline{X}_{ae}$
Fishing capacity	V_e^p	From Sardara
Canning capacity	V_e^p	From Sardara
Depreciation rate	η_e^p	Life of a boat : 10 years; $\eta_e^p = 0.10$
Investment rate	η_e^p	Half of income reinvested; $\eta_e^p = 0.5$
Demand function parameters for fresh and frozen tuna	a_f^p, b_f^p	From observed prices; $a_f^p = \overline{P}_f^p/2$, $b_f^p = \overline{P}_f^p/\overline{Q}_f^p$
Demand function parameters for canned tuna	a_c^p, b_c^p	From observed prices; $a_c^p = \overline{P}_c^p/2$, $b_c^p = \overline{P}_c^p/\overline{Q}_c^p$

Table A.1: Constants concerning nodes

A.2 Characteristics of stocks

Characteristics of stocks are given in tables A.3, A.4,A.5,A.6,A.7.

Table A.2: Constants concerning nodes and links

Parameter	Notation	Meaning and estimation
Fishing costs	C^p_{ae}	$C^p_{ae} = CF^p_{ae} + CK^p_{ae}/S_{ae}$; a part related to catches (CE), a part related to effort (CK; decreasing with fish abundance)
Canning costs	C^p_{fc}	from surveys (and from differences between observed prices)
Trading costs	C^{pq}_f	from surveys (and from differences between observed prices)
Trading costs	C^{pq}_c	from surveys (and from differences between observed prices)

Table A.3: Characteristics of the skipjack tuna (SKJ) stocks

Area	FAO area	X^p_{ae} (1000MT)	E^p_{ae} (100U.E.)	S_{ae} (1000MT)	K_{ae}	S_{ae}/K_{ae}	q^p_{ae}
64	WCP	381.9	56.5	1140.1	2280.2	0.5	5.9e-05
70	WCP	316.9	15.3	945.9	1891.8	0.5	0.000219
124	WI	74.3	3.8	170.6	487.3	0.35	0.001145
65	NWP	72.2	7.7	215.4	430.8	0.5	0.000435
69	WPC	45.8	2.2	136.7	273.3	0.5	0.001543
34	ECA	41	26.6	122.5	245	0.5	0.000126
16	ECP	38.7	3.7	115.5	230.9	0.5	0.000897
4	ECP	34.9	1.6	104.2	208.5	0.5	0.002049
22	WCA	28.9	8.5	86.4	172.7	0.5	0.000392
71	NWP	27	2.6	80.7	161.4	0.5	0.001286
118	WI	21.8	1.2	50.1	143.3	0.35	0.003591
21	SEP	18.4	0.5	55	110	0.5	0.006258
117	WI	16.1	2	36.9	105.4	0.35	0.00218
130	WI	15.1	0.9	34.7	99	0.35	0.005043
3	SWP	14.9	0.7	44.4	88.7	0.5	0.004658
10	ECP	13.9	0.5	41.4	82.8	0.5	0.006906
40	ECA	11.4	8.8	33.9	67.8	0.5	0.000381
63	WCP	10.5	1.9	31.3	62.7	0.5	0.001798
27	SWA	9.2	2.7	27.6	55.2	0.5	0.001253
15	SEP	8.8	0.1	26.3	52.6	0.5	0.053169
129	WI	7.9	0.7	18	51.5	0.35	0.006259
123	WI	7.2	1.2	16.6	47.5	0.35	0.003719
116	WI	7.2	0.8	16.4	47	0.35	0.005481
142	EI	7.1	0.2	16.3	46.6	0.35	0.026794
136	WI	6.9	0.4	15.9	45.5	0.35	0.009953
17	NEP	6.8	1.4	20.3	40.6	0.5	0.002355
131	WI	6.2	0.1	14.3	40.8	0.35	0.085753
9	SWP	5.9	0.4	17.6	35.2	0.5	0.007553
125	WI	4.3	0.1	9.9	28.2	0.35	0.058819

The skipjack tuna (Table A.3) is known as the more distributed species through worldwide ocean. This species is fully exploited in the Indian ocean and moderately fished in the Pacific and Atlantic oceans. With a short lifespan and a high coefficient of rebuilding stocks, this species is not actually endangered. Their stocks are globally healthiness. The catchability coefficient as well as the carrying capacity for the IO stocks are higher than those of Atlantic and Pacific ocean.

Table A.4: Characteristics of the yellowfin tuna (YFT) stocks

Area	FAO area	X^p_{ae} (1000MT)	E^p_{ae} (100U.E.)	S_{ae} (1000MT)	K_{ae}	S_{ae}/K_{ae}	q^p_{ae}
16	ECP	140	5.5	603.4	3017.1	0.2	0.000419
70	WCP	86.1	12.1	456.8	1305.1	0.35	0.000156
64	WCP	71.9	65.4	381.4	1089.8	0.35	2.9e-05
124	WI	53.5	6.1	230.4	1152.2	0.2	0.00038
22	WCA	52.6	9	279.1	797.5	0.35	0.000209
10	ECP	41.9	4.1	180.6	903.1	0.2	0.000563
34	ECA	36.9	27.1	195.8	559.4	0.35	7e-05
118	WI	29.8	3.1	128.4	641.8	0.2	0.000745
9	SWP	25.6	5.9	135.9	388.2	0.35	0.000322
117	WI	25.3	2.8	109	545.1	0.2	0.000837
21	SEP	23.8	0.6	102.5	512.3	0.2	0.003878
130	WI	23.1	3	99.7	498.5	0.2	0.000778
40	ECA	18.1	8.3	96.2	274.8	0.35	0.000227
129	WI	17.7	1.3	76.2	380.8	0.2	0.001767
123	WI	17.2	1.9	74.1	370.7	0.2	0.001214
4	ECP	17.1	2.2	73.7	368.4	0.2	0.001044
69	WCP	16.7	2.8	88.7	253.3	0.35	0.000685
15	SEP	16.6	1.4	71.6	357.9	0.2	0.001645
63	WCP	8.4	12.9	44.5	127.1	0.35	0.000146
17	ECP	8.4	1.3	36.1	180.3	0.2	0.001763
116	WI	6.5	1	28.1	140.4	0.2	0.002433
39	SEA	6.3	1.5	33.6	96	0.35	0.001249
28	WCA	6.1	2.8	32.5	92.9	0.35	0.000681
132	WI	5.9	0.2	25.6	128.1	0.2	0.013899
136	WI	5.6	0.5	24.1	120.4	0.2	0.004839
65	NWP	4.9	4.6	26.2	74.7	0.35	0.000413
125	WI	4.5	0.2	19.4	96.8	0.2	0.011185
131	WI	3.8	0.2	16.4	82.1	0.2	0.013264
135	WI	3.7	0.3	15.9	79.3	0.2	0.006644

The yellowfin (Table A.4) is the second more distributed tuna species after the skipjack. In contrast to skipjack, the yellow fin tuna is overfished in both Indian and eastern Pacific ocean and fully exploited in both western Pacific and Atlantic ocean. Its lifespan is quite long, hence its stocks take time to rebuild. This species is listed as endangered.

It is not a surprise to see that all stocks of bigeye tuna (Table A.5) are fully exploited. Its lifespan is long and gets the maturity quite late. Bigeye tuna is listed as a vulnerable species.

The albacore stocks (Table A.6) are the most diversified stocks of tuna species in terms of exploitation. The north Atlantic stock is overfished while the ones of the whole Pacific are moderately exploited. Both the west Indian and the south Atlantic (east to west) are fully exploited.

Table A.5: Characteristics of the bigeye tuna (BET) stocks

Area	FAO area	X^p_{ae} (1000MT)	E^p_{ae} (100U.E.)	S_{ae} (1000MT)	K_{ae}	S_{ae}/K_{ae}	q^p_{ae}
9	SWP	57.9	5.1	307.1	877.3	0.35	0.000367
10	ECP	50.5	3.7	267.8	765.3	0.35	0.000504
124	WI	35.4	6.1	187.8	536.6	0.35	0.000308
130	WI	28	3.1	148.6	424.7	0.35	0.000606
16	ECP	26.8	0.9	142.3	406.5	0.35	0.002198
15	SEP	25.7	1.6	136.6	390.1	0.35	0.001166
34	ECA	24.2	29	128.6	367.5	0.35	6.5e-05
118	WI	20.7	2.6	109.6	313.1	0.35	0.000725
70	WCP	18.1	10.3	96.2	274.9	0.35	0.000183
64	WCP	13	11.1	68.9	196.8	0.35	0.00017
33	SEA	12.3	1.9	65.4	186.8	0.35	0.001016
117	WI	10.7	3.6	57	162.8	0.35	0.000519
123	WI	9.8	2.8	51.8	148	0.35	0.000672
4	ECP	9.7	2.2	51.5	147.1	0.35	0.000844
129	WI	8.4	2	44.5	127.1	0.35	0.00095
28	WCA	7.4	0.6	39.4	112.6	0.35	0.00319
39	SEA	7.3	1.8	38.9	111	0.35	0.00104
21	SEP	7	1	37.3	106.6	0.35	0.001902
22	WCA	7	3.1	36.9	105.5	0.35	0.000609
69	WCP	5.4	4.2	28.9	82.6	0.35	0.000447
136	WI	5.2	1	27.5	78.5	0.35	0.001885
141	EI	5	0.4	26.3	75.2	0.35	0.004614
142	EI	4.9	0.5	26.1	74.5	0.35	0.003891
40	ECA	4.7	8.3	25.1	71.7	0.35	0.000227
135	WI	4.5	0.9	24	68.6	0.35	0.002152
63	WCP	3.7	1	19.4	55.4	0.35	0.001983

Table A.6: Characteristics of the albacore (ALB) stocks

Area	FAO area	X^p_{ae} (1000MT)	E^p_{ae} (100U.E.)	S_{ae} (1000MT)	K_{ae}	S_{ae}/K_{ae}	q^p_{ae}
71	NWP	18.6	2.4	92.9	185.7	0.5	0.000838
130	WI	16	0.7	61.6	175.9	0.35	0.003984
9	SWP	15.8	4.4	78.9	157.8	0.5	0.000451
4	ECP	10.6	5.7	53.1	106.1	0.5	0.00035
69	WCP	10.3	0.8	51.6	103.2	0.5	0.00248
33	SEA	7.3	1	27.9	79.8	0.35	0.00251
65	NWP	5.2	2.5	26.2	52.5	0.5	0.000791
35	NEA	5.1	4.3	16	80.1	0.2	0.000737
117	WI	4.9	4.9	18.9	53.9	0.35	0.00053
68	SWP	4.7	0.3	23.3	46.7	0.5	0.00683
70	WCP	4.6	1	23.1	46.2	0.5	0.002017
124	WI	4	2.1	15.4	43.9	0.35	0.001251
27	SWA	3.7	2.9	14	40.1	0.35	0.000889
39	SEA	3.5	0.5	13.4	38.4	0.35	0.005485

Table A.7: Characteristics of the Northern bluefin tuna (BFT) stocks

Area	FAO area	X^p_{ae} (1000MT)	E^p_{ae} (100U.E.)	S_{ae} (1000MT)	K_{ae}	S_{ae}/K_{ae}	q^p_{ae}
17	NEP	8.1	1.4	101.3	506.3	0.2	0.000575
35	NEA	6.5	5.5	81.3	406.4	0.2	0.000147

The bluefin tuna stocks(Table A.7) are the most endangered stocks of tuna species. This species is few distributed, its catches are high, its lifespan very long, and it is obviously threating.

A.3 Characteristics of tuna markets

They are given in table A.8.

Table A.8: The demand on the FF markets

Species	country	consumption L (MT)	import (MT)	export (MT)	P (US dol/kg)	a	b
ALB	ESP	0	19460	2554	1.92	3.85	–
ALB	JPN	7959	0	28187	2.15	4.3	0.27
ALB	THA	5500	16896	11396	1.91	3.82	0.35
ALB	TWN	0	0	49834	2.14	4.28	–
ALB	USA	0	49218	857	2.54	5.09	–
BET	JPN	78498	89053	14732	5.05	10.09	0.06
BET	TWN	0	0	71059	5.87	11.74	–
BFT	JPN	2449	0	0	NaN	NaN	NaN
SKJ	ESP	0	46071	59960	0.81	1.62	–
SKJ	FRA	0	5700	72938	0.79	1.58	–
SKJ	IDN	88017	0	29215	0.82	1.65	0.01
SKJ	JPN	98442	42610	58394	0.83	1.66	0.01
SKJ	KOR	0	20818	20818	0.6	1.21	–
SKJ	MAR	9056	9056	0	0.91	1.82	0.1
SKJ	PHL	0	23552	10297	0.66	1.31	–
SKJ	THA	302844	315729	12884	0.87	1.74	0
SKJ	TWN	0	0	188056	0.64	1.28	–
SKJ	USA	11443	18015	6572	1.07	2.14	0.09
SKJ	VEN	3352	0	8632	0.29	0.58	0.09
TUN	USA	0	0	0	NaN	NaN	NaN
TUN	ECU	0	9146	1822	0.53	1.05	–
TUN	ESP	0	13489	4467	1.39	2.77	–
TUN	IDN	44839	0	29407	2.87	5.74	0.06
TUN	JPN	4099	638	17169	2.33	4.67	0.57
TUN	KOR	153980	0	20386	3.57	7.13	0.02
TUN	MEX	54	353	17285	1.42	2.85	26.35
TUN	PHL	0	18693	0	0.67	1.34	–
TUN	SYC	12747	23841	11094	0.68	1.36	0.05
TUN	THA	0	67854	0	0.98	1.95	–
TUN	TWN	0	390	17496	3.76	7.52	–
YFT	JPN	0	13213	13213	0	0	NaN
YFT	COL	0	2397	33332	1.02	2.03	–
YFT	ESP	0	77871	47838	1.2	2.4	–
YFT	FRA	0	8631	65850	1.24	2.47	–
YFT	IDN	19319	0	16698	2.09	4.17	0.11
YFT	ITA	21923	30943	9020	1.62	3.24	0.07
YFT	JPN	71615	83259	17322	2.48	4.97	0.03
YFT	KOR	6030	1380	39452	2.06	4.12	0.34
YFT	MAR	2917	7953	5036	0.81	1.63	0.28
YFT	MEX	53	758	18493	0.97	1.94	18.34
YFT	THA	0	121129	0	1.13	2.25	–
YFT	TWN	0	0	95348	3.41	6.81	–
YFT	USA	0	16655	1015	3.01	6.01	–
YFT	VEN	38001	0	11732	0.88	1.75	0.02

Table A.9: The demand on the prepared markets

Species	country	consumption L (MT)	import (MT)	export (MT)	P (US dol/kg)	a	b
ALB	USA	46849	0	0	NaN	NaN	NaN
SKJ	CAN	1253	1253	0	3.25	6.5	2.6
SKJ	GER	618	754	136	2.44	4.89	3.96
SKJ	IDN	32301	0	3729	2.73	5.45	0.08
SKJ	JPN	17461	7399	2210	3.81	7.62	0.22
SKJ	PHL	914	0	6413	2.08	4.16	2.28
SKJ	THA	76159	0	0	NaN	NaN	NaN
SKJ	UK	1497	1841	344	2.68	5.36	1.79
SKJ	USA	65140	180	0	0.62	1.25	0.01
TUN	BRA	0	977	2751	2.72	5.44	–
TUN	CAN	0	9054	9054	3.04	6.08	–
TUN	COL	0	7818	14847	2.54	5.08	–
TUN	ECU	1369	0	57172	2.45	4.91	1.79
TUN	ESP	101869	15675	73145	3.68	7.37	0.04
TUN	FRA	63345	89592	43337	2.92	5.85	0.05
TUN	GER	23825	52707	28883	2.76	5.52	0.12
TUN	IDN	0	16739	16739	2.22	4.45	–
TUN	ITA	33007	59367	26360	4.38	8.76	0.13
TUN	JPN	127528	16813	16336	5.11	10.22	0.04
TUN	KOR	0	473	473	3.33	6.66	–
TUN	MEX	32962	0	17684	2.38	4.75	0.07
TUN	NET	0	19803	19803	2.49	4.99	–
TUN	PHL	3531	1944	35259	2.01	4.02	0.57
TUN	SYC	0	0	12369	3.78	7.56	–
TUN	THA	0	115805	189464	2.04	4.09	–
TUN	TWN	0	647	2802	1.25	2.49	–
TUN	UK	75799	96015	20216	2.77	5.54	0.04
TUN	USA	144047	114403	18359	2.35	4.69	0.02
TUN	VEN	667	448	13227	1.15	2.29	1.72

Appendix B

Computation and R language

B.1 The computation process of the system equilibrium

The current section aims to outline the main stages leading to the computation of the system equilibrium. We have seen in chapter 6 that we have to solve linear complementarity problem associated to a linear function characterized by a matrix M and a vector N.F

From the matrix and the vector built, some functions must be first defined in order to reduce the system complexity. To solve the system, an algorithm has been called. This is *the interior point algorithm* from Facchinei and Pang (2003). All the methodology followed here is based on that book.

B.1.1 Defining functions

All the following functions are defined in order to simplify the complexity of the system. The problem will be solved using an algorithm that calls these functions. The variables X and Y that will be fixed at the beginning of each simulation are considered as the two specific arguments of these functions. Here are the main functions used:

1. Function F: $X \to F(X) = M.X + N$ returns a vector that will be served to test the solution of the system

2. Function E: $(X, Y) \to E(X) = Y - F(X)$ returns a vector. It is a complementary function and will be called inside the algorithm through other functions

3. Function ρ: $(X,Y) \to \rho(X,Y)$ provides a positive and non null value. It serves to define other functions as well as to run the simulation.

$$\begin{aligned}\rho(X,Y) &= \sum_i x_i^2 y_i^2 + \sum_i (y_i - (\sum_j m_{ij} x_j + q_i))^2 \\ &= \|XY\|^2 + \|E(X,Y)\|^2\end{aligned}$$

4. Function ψ: $(X,Y) \to \psi(X,Y)$ also provides a positive and non null value.

$$\psi(X,Y) = \zeta \lg(\rho(X,Y)) - \sum_i \lg(x_i y_i) - \sum_i \lg(y_i - (\sum_j m_{ij} x_j + q_i))$$

5. Function $\nabla\psi$: $(X,Y) \to \nabla\psi(X,Y)$ gives back a vector twice longer than other vectors. This function makes the algorithm more efficient by saving the running time.

$$\nabla\psi(X,Y) = \begin{pmatrix} \dots \\ \frac{1}{x_i} - \sum_j \frac{m_{ji}}{e_j} - \frac{(x_i y_i^2 - \sum_j m_{ji} e_j)2\zeta}{\rho(X,Y)} \\ \dots \\ \frac{1}{y_i} + \frac{1}{e_i} - \frac{(x_i^2 y_i + e_i)2\zeta}{\rho(X,Y)} \\ \dots \end{pmatrix}$$

$$\nabla\psi(X,Y) = \begin{pmatrix} \frac{1}{X} -^T M.\frac{1}{E} - \frac{2\zeta}{\rho(X,Y)}(XY^2 -^T M.E) \\ \frac{1}{Y} + \frac{1}{E} - \frac{2\zeta}{\rho(X,Y)}(X^2Y + E) \end{pmatrix}$$

6. Function G: $(X,Y) \to G(X,Y)$ provides a vector the same length as the one created by the function $\nabla\psi(X,Y)$

$$G(X,Y) = \begin{pmatrix} \dots \\ x_i y_i \\ \dots \\ y_i - (\sum_j m_{ij} x_j + q_i) \\ \dots \end{pmatrix}$$

$$G(X,Y) = \begin{pmatrix} XY \\ E(X,Y) \end{pmatrix}$$

7. Function JG: $(X,Y) \rightarrow JG(X,Y)$ gives back a large square matrix combining four matrices. $D(Y)$ and $D(X)$, are the diagonal matrix of the vectors X and Y, respectively. $D(U)$ is the diagonal matrix obtained from an unit vector. The dimension of the matrix JG is the double of the one of the matrix M

$$JG(X,Y) \quad = \quad \begin{pmatrix} D(Y) & D(X) \\ -M & D(U) \end{pmatrix}$$

B.1.2 Algorithm to solve the problem

It is as follows.

B.1.2.1 (1) Initialization

- $\gamma \leftarrow 0.1$
- $\sigma \leftarrow 0.5$
- $\zeta \leftarrow 2n$
- $\varepsilon \leftarrow 0.000001$
- $U = (1, \ldots, 1)$ with length n
- $A = (1, \ldots, 1)$ with length $2n$
- $X_s \leftarrow PositiveRandomVector$
- $Y_s \leftarrow Max(X_s, F(X_s)$
- $G_s \leftarrow G(X_s, Y_s)$

B.1.2.2 (2) Loop

- If $(\|G_s\| > \varepsilon)$ Repeat
  1. $JG_s \leftarrow JG(X_s, Y_s)$

2. $Q_s \leftarrow -G_s + (\sigma A.Gs/A.A)A$
3. $(DX_s, DY_s) \leftarrow LinearSolve(JG_s, Q_s)$
4. $\mu \leftarrow 2$
5. Repeat $\mu \leftarrow \mu/2$ until
   $(X_s + \mu DX_s > 0)$ and $(Y_s + \mu DY_s > 0)$ and
   $(Y_s + \mu DY_s > F(X_s + \mu DX_s))$ and
   $\psi(X_s + \mu DX_s, Y_s + \mu DY_s) < \psi(X_s, Y_s) + \gamma\mu(DX_s \nabla\psi_x(X_s, Y_s) + DY_s \nabla\psi_y(X_s, Y_s)$
6. $X_s \leftarrow X_s + \mu DX_s$
7. $Y_s \leftarrow Y_s + \mu DY_s$
8. $G_s \leftarrow G(X_s, Y_s)$
9. Until $(\|G_s\| \leq \varepsilon)$

- Return(X_s)

To summarize why an algorithm is necessarily used and what do we expect, see the following items.

- The Newton algorithm is here used to solve the large problem that shapes the model. The method used is based on the Rui and Xu (2010)'s work that is applied for solving the linear complementarity problem. The system $F(X) = M \times X + N$ aims to determine $X \in R^n$. Where $X \geq 0$, $F(X) \geq 0$, and $X^t F(X) = 0$ (a complementarity relationship) with $F : K \to R^n_+ \times R^n_+$ (with K a convex set) are a continuously differentiable function and t the number of iterations.

- The solution of the system must verify the variational inequality relationship (see appendix). The variational inequality $VI(F, K)$ problem consists in founding $X^* \in K$ such that for all $X \in K$, $(X - X^*).F(Z) \geq 0$. Then $X^* \in K$ is an equilibrium state if and only if it is a solution of the variational inequality.

- For the specific algorithm described here, at the end of simulation, the solution X_s is given back. The problem shows in the algorithm is like a minimization problem. The xi_s elements must be positive and small. The value obtained for the vector X_s must also confirm the complementarity relationship.

B.2 Launching the algorithm on R

B.2.1 Test with a symmetric small scale matrix (on R)

Here the algorithm is tested on a small scale matrix in order to present confirmation of all conditions described above. The matrix M is a symmetric square matrix with dimensions 10 by 10 and the vector N with 10 elements. At the beginning of the simulation we put $X = (-1 ... -1)$

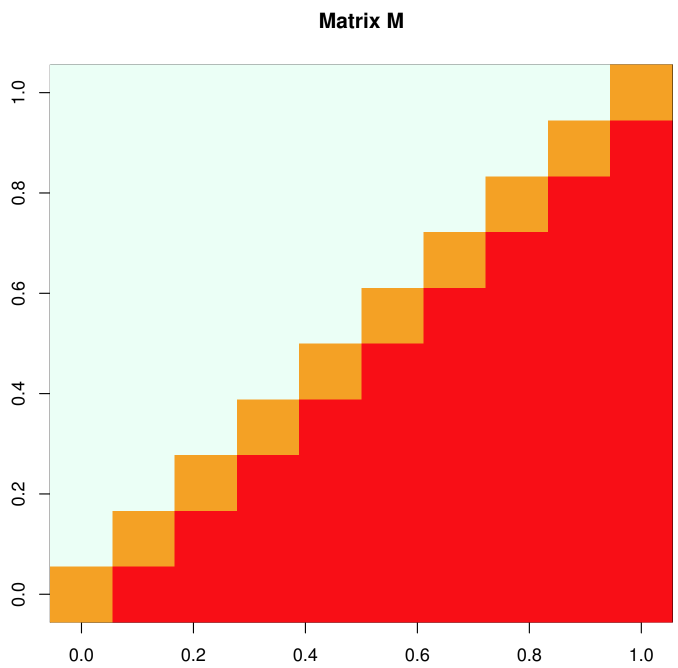

Figure B.1: The small scale matrix M

Table B.1: The simulation results for a small scale matrix

Number of rows	X	$F(X)$	$F(X) \times X$
1	0	1	0
2	0	1	0
3	0	1	0
4	0	1	0
5	0	1	0
6	0	1	0
7	0	1	0
8	0	1	0
9	0	1	0
10	1	0	0

After running the algorithm, results are showed in the table B.1. These results verify the variational inequality relationship where X the solution of the system is well an equilibrium state.

B.2.2 Solution for the large matrix

As seen above, the matrix M is a large sparse matrix. For this kind of matrix a specific transformation in the matrix format is necessary for a without error running. In R, by charging the package *Matrix*, the function **Matrix** is then called (see http://Matrix.R-forge.R-project.org/). The large matrix that is generated by the function JG (defined above) is converted by the function **Matrix**. This conversion allows the algorithm solution, if there is convergence, to be possible and very efficient. Once running, at the end of simulation, the solution of the system called X_s is obtained. It corresponds to the equilibrium state of the system. The solution for such system is summarized in the figure B.2.2. When using the matrix M, the vector N, the initial value of the vector solution $X0$, other model parameters already indicated, and by following all the required process the solution of the system X_s find include most of values equal or near to zero. Most of values obtained from $F(Xs) * Xs$ also confirm the VI relationship, in other words, the solution of the system is obviously an equilibrium state.

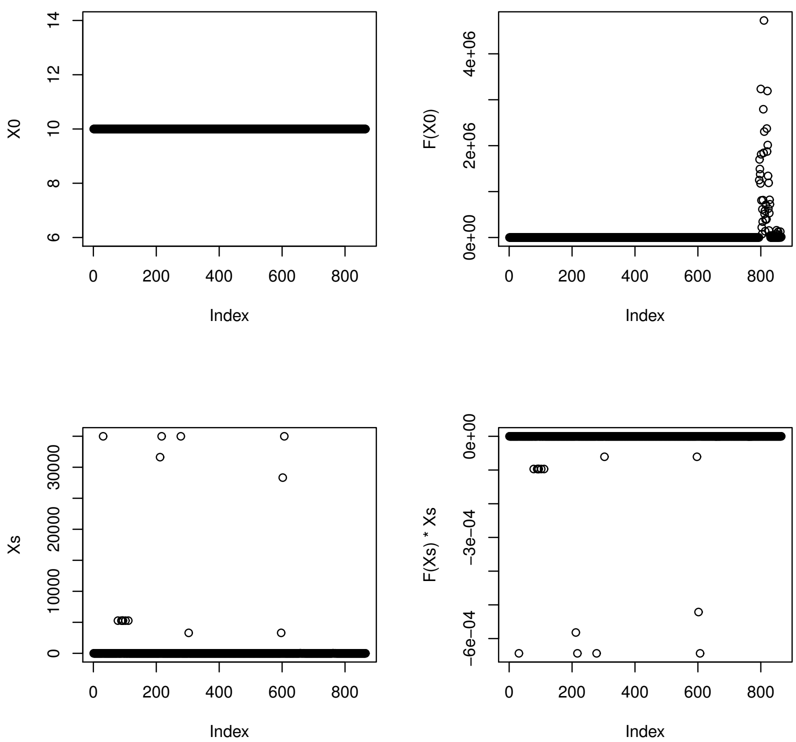

Figure B.2: The initial value of $X0$ (top left), the solution of the system Xs (down left), the $F(X0)$ initial value of the function (top right) and the relationship $F(Xs) * Xs$ (down right)

B.3 Code of the program in R

```
#---------------------------------------------------
# A Charging data
#---------------------------------------------------
# Data for all links
#---------------------------------------------------
CA<-read.table("FF_Link_AEP.CSV", dec=".", sep=",", header=T)
PF<-read.table("FF_Link_EFP.CSV", dec=".", sep=",", header=T)
PC<-read.table("FF_Link_FCP.CSV", dec=".", sep=",", header=T)
TF<-read.table("FF_Link_FPP.CSV", dec=".", sep=",", header=T)
TC<-read.table("FF_Link_CPP.CSV", dec=".", sep=",", header=T)
SC<-read.table("FF_Link_CPCPm.CSV", dec=".", sep=",", header=T)
SF<-read.table("FF_Link_FPFPm.CSV", dec=".", sep=",", header=T)
#---------------------------------------------------
# Data for all nodes
#---------------------------------------------------
ST<-read.table("FF_Node_Stocks_AE.CSV", dec=".", sep=",", header=T)
FL<-read.table("FF_Node_Fleets_EP.CSV",dec=".", sep=",", header=T)
PuF<-read.table("FF_Node_Production_FP.CSV", dec=".", sep=",", header=T)
PuC<-read.table("FF_Node_Production_CP.CSV",dec=".", sep=",", header=T)
MF<-read.table("FF_Node_FPm.CSV", dec=".", sep=",", header=T)
MC<-read.table("FF_Node_CPm.CSV", dec=".", sep=",", header=T)
#------------------------------------------------------------------
# B reating the matrix and the vector
#-----------------------------------------------------------------
#For links
#---------------------------------------------------
ca<-NROW(CA);pf<-NROW(PF);pc<-NROW(PC);sf<-NROW(SF)
sc<-NROW(SC);tc<-NROW(TC);tf<-NROW(TF)
L<- ca + pf + pc + tf + tc + sf + sc
#---------------------------------------------------
#For nodes
#---------------------------------------------------
fl<-NROW(FL); puc<-NROW(PuC); puf<-NROW(PuF)
#---------------------------------------------------
# To increment
#---------------------------------------------------
fu<-fl+puf; q<-ca+pf; fl1<-fl+1 ; ca1<- ca+1; q1<-ca+pf+1
uc<-ca+pf+pc; fu<-fl+puf; fu1<-fu+1; uc1<-uc+1; utf<-uc+tf
utc<-utf + tc; tf1<-utf+1;
utf1<-utf+1; utc1<-utc+1; usf<-utc+sf; usf1<-usf+1
#-------------------------------------------------------
# Create the matrix of links
#---------------------------------------------------
MLL<-matrix(0, nrow=L, ncol=L)
ML1<-matrix(0, nrow=sf, ncol=sf)
for (m in 1:nrow(MF))
{
ML1[MF$nfp[m], MF$nfp[m]]<-MF$b[m]
}
ML2<-matrix(0, nrow=sc, ncol=sc)
for (n in 1:nrow(MC))
{
ML2[MC$ncp[n], MC$ncp[n]]<-MC$b[n]/2
}
MLL[utc1:usf , utc1: usf]<-ML1
MLL[usf1: L, usf1 :L]<-ML2
#-------------------------------------------------------
# Create a matrix with links in lines and nodes in columns
#---------------------------------------------------
N<-NROW(FL) + NROW(PuF)+ NROW(PuC)
MLN<-matrix(0, nrow=L, ncol=N)
```

```
#---------------------------------------------------
# 1)destination of fishing species
#---------------------------------------------------
for (l in 1:ca)
{
MLN[l,CA$nep[l]]<- -1
}
#---------------------------------------------------
# 2)For fleets nodes and FF links
#destination
#---------------------------------------------------
LN1<-matrix(0, nrow=pf, ncol=puf)
for (w in 1:pf)
{
LN1[w,PF$nfp[w]]<- -1
}
MLN[ca1:q, fl1:fu] <-LN1
#---------------------------------------------------
#View(MLN[1: 200, 1:50])
# origin
#---------------------------------------------------
LN10<-matrix(0, nrow=pf, ncol=fl)
for (w in 1:pf)
{
LN10[w,PF$nef[w]]<- 1
}
MLN[ca1:q, 1:fl] <-LN10
#---------------------------------------------------
# 2)For canning nodes and canned production links
#destination
#---------------------------------------------------
LN2<-matrix(0, nrow=pc, ncol=puc)
for (x in 1:pc)
{
LN2[x,PC$ncp[x]]<- -1
}
MLN[q1:uc, fu1:N]<- LN2
#---------------------------------------------------
#View(MLN[1: 200, 1:50])
# origin
#---------------------------------------------------
LN20<-matrix(0, nrow=pc, ncol=puf)
for (x in 1:pc)
{
LN20[x,PC$nfp[x]]<- 1
}
MLN[q1:uc, fl1:fu] <-LN20
#---------------------------------------------------
#3)For fresh and frozen trading
# destination
#---------------------------------------------------
LNtf<-matrix(0, nrow=tf, ncol=puf)
for (y in 1:tf)
{
LNtf[y,TF$nfq[y]]<- -1
}
#---------------------------------------------------
#origin
#---------------------------------------------------
LNtf0<-matrix(0, nrow=tf, ncol=puf)
for (y in 1:tf)
{
LNtf0[y,TF$nfp[y]]<- 1
```

```
}
MLN[uc1:utf, fl1:fu] <-LNtf + LNtf0
#---------------------------------------------------
# 4) For canned trading
# destination
#---------------------------------------------------
LNtc<-matrix(0, nrow=tc, ncol=puc)
for (z in 1:tc)
{
LNtc[z,TC$ncq[z]]<- -1
}
#---------------------------------------------------
# origin
#---------------------------------------------------
LNtc0<-matrix(0, nrow=tc, ncol=puc)
for (z in 1:tc)
{
LNtc0[z,TC$ncp[z]]<- 1
}
MLN[utf1:utc, fu1:N] <- LNtc+ LNtc0
#---------------------------------------------------
# 5) Origin and destination in both markets
#---------------------------------------------------
LNfm<-matrix(0, nrow=sf, ncol=puf)
for (si in 1:sf)
{
LNfm[si,si]<- 1
}
MLN [utc1:usf, fl1:fu] <- LNfm
LNcm<-matrix(0, nrow=sc, ncol=puc)
for (se in 1:sc)
{
LNcm[se,se]<- 1
}
MLN [usf1:L, fu1:N] <- LNcm
#-----------------------------------------------------
# Create a matrix with links in lines and constrained nodes in columns
#---------------------------------------------------
Q<- NROW(FL) + NROW(PuC)
MLQ<-matrix(0, nrow=L, ncol=Q)
MQL<-matrix(0, nrow=L, ncol=Q)
for (l in 1:ca)
{
MLQ[l,CA$nep[l]]<-1
}
MLQ[MLQ==Inf]<-0
MQ<-matrix(0, nrow=pc, ncol=puc)
for (x in 1:pc)
{
MQ[x, PC$ncp[x]]<-1
}
MLQ[q1:uc, fl1:Q ]<-MQ
MLQ[MLQ==Inf]<-0
for (l in 1:ca)
{
MQL[l,CA$nep[l]]<- -1/(ST$Stock[CA$nae[l]] * ST$q[CA$nae[l]])
}
MQL[MQL==Inf]<-0
MQ<-matrix(0, nrow=pc, ncol=puc)
for (x in 1:pc)
{
MQ[x, PC$ncp[x]]<- -1
}
```

```
MQL[q1:uc, fl1:Q ]<-MQ
MQL[MQL==Inf]<-0
#----------------------------------------------------
# Transposed matrices of MLG and MLQ
#----------------------------------------------------
MNL<- -t(MLN)
MQL<- t(MQL)
#---------------------------------------------------------
# Create the final matrix
#----------------------------------------------------
D<-L+N+Q
MM <- matrix(0, nrow=D, ncol=D)
MM[1:L, 1:L] <-MLL
MM[1:L, (L+1):(L+N)] <-MLN
MM[1:L, (L+N+1):D] <-MLQ
MM[(L+1):(L+N), 1:L] <-MNL
MM[(L+N+1):D, 1:L] <-MQL
MM[MM==Inf]<-0
MM[MM==NA]<-0
#-------------------------------------------------------------
#Building the vector
#-------------------------------------------------------------
NL<-array(0, L)
ca<- NROW(CA)
ca1<-ca +1
for (l in 1:ca)
{
NL[l]<-(CA$cY[l]+ ST$pr[CA$nae[l]] + CA$cE[l]*
(ST$Stock.Init[CA$nae[l]]/ST$Stock[CA$nae[l]]))
}
NL[(ca+1): utc]<-(c(PF$costs, PC$costs, TF$costs, TC$costs))
NL1<-array(0, nrow(SF) )
NL2<-array(0,nrow(SC))
NL1<- SF$costs
for (m in 1:nrow(MF))
{
NL1[MF$nfp[m]]<- (SF$costs[MF$nfp[m]] - MF$a[m])
}
NL2<- SC$costs
for (n in 1:nrow(MC))
{
NL2[MC$ncp[n]]<- (SC$costs[MC$ncp[n]] - MC$a[n]/2)
}
NL[utc1: usf]<-NL1
NL[usf1: L] <-NL2
#----------------------------------------------------
# To create a zero vector
#----------------------------------------------------
NO<-array(0,N)
#----------------------------------------------------
# To create a vector with capacities values
#----------------------------------------------------
Q<-NROW(FL) + NROW(PuC)
NQ<-array(0, Q)
NQ <-c(FL$fishing.capacity, PuC$canning.capacity)
#------------------------------------------------------
# Create the final vector NN
#----------------------------------------------------
D<-L+N+Q
NN<-array(0,D)
NN[1:L]<-NL
NN[(L+1):(N+L)] <- NO
NN[(L+N+1): D] <- NQ
```

```
NN[NN==Inf]<-0
NN[NN==NA]<-0
#--------------------------------------------------------------
#Code R to compute the system equilibrium
#--------------------------------------------------------------
M<-MM
Q<-NN
#---------------------------------------------------
# Defining functions
#---------------------------------------------------
F<-function(X){
return (as.numeric(M*X)+ Q)
}
#---------------------------------------------------
E<-function(X,Y)
{
E=Y-F(X)
return (as.numeric(E))
}
#---------------------------------------------------
norm<-function(V)
{
return (sqrt(V %*% V))
}
#---------------------------------------------------
rho<-function(X, Y)
{
rho<- as.numeric((norm(X*Y))^2 + (norm(E(X,Y)))^2)
return (rho)
}
#---------------------------------------------------
loge<-function(X)
{
loge<-log(X)
loge[loge==-Inf]<-0
loge[loge==NA]<-0
return(loge)
}
#---------------------------------------------------
psi<-function(X,Y)
{
psi<-zeta*log(rho(X,Y))-sum(log(X*Y))-sum(loge(E(X,Y)))
return (psi)
}
#---------------------------------------------------
invE<- function(X,Y)
{
invE<-1/E(X,Y)
invE[invE==Inf]<-0
invE[invE==NA]<-0
return (invE)
}
#---------------------------------------------------
Vs1<- function (X,Y)
{
return (as.numeric(1/X-(as.numeric(t(M)%*%invE(X,Y))))-
(2*zeta/rho(X,Y)*(X*Y^2-as.numeric(t(M)%*%E(X,Y)))) )
}
#---------------------------------------------------
Vs2<- function (X,Y)
return ((1/Y) + invE(X,Y) -(2*zeta/rho(X,Y)*(X^2*Y + E(X,Y))))
#---------------------------------------------------
nabpsi<-function(X, Y)
```

```
{
nabpsi<- c(Vs1(X,Y), Vs2 (X,Y))
return (nabpsi)
}
#---------------------------------------------------
G<-function(X,Y)
{
G<-as.numeric(c(X*Y, E(X,Y)))
return (G)
}
#---------------------------------------------------
library(Matrix)
JG<-function(X,Y)
{
DY<-diag(Y)
DX<-diag(X)
mat<-matrix(0, nrow=(lin2), ncol=(lin2))
mat[1:lin, 1:lin2]<-c(DY,DX)
mat[(lin+1):lin2, 1:lin2 ]<- c(-M, diag(U))
return (Matrix(mat))
}
#---------------------------------------------------
# Algorithm to solve the system
#---------------------------------------------------
lin<-nrow(M)
U<-array(1, lin)
gamma<-0.1
sigma<-0.5
zeta<-2*lin
lin2<-2*lin
A<-array(1,zeta)
epsilon<-0.000001
Xs<-as.numeric(array(10,lin))
Ys<-as.numeric(array(0,lin))
for (i in 1:lin)
{
Ys[i]<-max(Xs[i], F(Xs)[i])
}
Gs<-G(Xs, Ys)
if (norm(Gs) >= epsilon)
{
repeat
{
JGs<-JG(Xs,Ys)
Qs<-as.numeric(-Gs+ as.numeric((sigma*A%*%Gs/A%*%A))*A)
DZ<- solve(JGs, Qs)
DXs<-DZ[1:lin]
DYs<-DZ[(lin+1):zeta]
mu<-2
Vs<-(DXs%*%Vs1(Xs,Ys) + DYs%*%Vs2(Xs,Ys))
repeat
{
  mu<-mu/2
if ( (min(Xs + (mu*DXs)) >0) &&
(min(Ys + (mu*DYs)) >0) &&
(min((Ys+ (mu*DYs))-(F(Xs+(mu*DXs))))>0) &&
(psi(Xs+(mu*DXs), Ys+(mu*DYs))< as.numeric(psi(Xs,Ys)+ gamma*mu*Vs))
)
break
}
Xs<-Xs + (mu*DXs)
Ys<-Ys + (mu*DYs)
Gs<-G(Xs,Ys)
```

```
if (norm(Gs) < epsilon ) break
}
}
#---------------------------------------------------------------
#Code to compute the system dynamics
#---------------------------------------------------------------
Xmin<-Xs
#---------------------------------------------------------------
# for links
#---------------------------------------------------------------
Xca<-matrix(0, nrow=max(CA$nae), ncol=max(CA$nep))
for (l in 1:ca)
{
Xca[CA$nae[l], CA$nep[l]] <-Xmin[l]
}
Xpf<-matrix(0, nrow=max(PF$nef), ncol=max(PF$nfp))
for (w in 1:pf)
{
Xpf[PF$nef[w], PF$nfp[w]]<-Xmin[ca1:q][w]
}
Xpc<-matrix(0, ncol=max(PC$nfp), nrow=max(PC$ncp))
for (x in 1:pc)
{
Xpc[PC$ncp[x], PC$nfp[x]] <-Xmin[q1:uc][x]
}
Xtf<-matrix(0, nrow=max(TF$nfp), ncol=max(TF$nfq))
for (y in 1:tf)
{
Xtf[TF$nfp[y], TF$nfq[y]] <-Xmin[uc1:utf][y]
}
Xtc<-matrix(0, nrow=max(TC$ncp), ncol=max(TC$ncq))
for (z in 1:tc)
{
Xtc[TC$ncp[z], TC$ncq[z]] <-Xmin[utf1:utc][z]
}
Xsf<-matrix(0, nrow=max(SF$nf), ncol=max(SF$np))
for (si in 1:sf)
{
Xsf[SF$nf[si], SF$np[si]] <-Xmin[utc1:usf][si]
}
Xsc<-matrix(0, nrow=max(SC$nc), ncol=max(SC$np))
for (se in 1:sc)
{
Xsc[SC$nc[se], SC$np[se]] <-Xmin[usf1:L][se]
}
#---------------------------------------------------------------
# For nodes
#---------------------------------------------------------------
N<-NROW(FL) + NROW(PuF)+ NROW(PuC)
Xfl<-matrix(0, nrow=max(FL$ne), ncol=max(FL$np))
for (f in 1:fl)
{
Xfl[FL$ne[f], FL$np[f]] <-Xmin[(L+1):(L+fl)][f]
}
Xpuf<-matrix(0, nrow=max(PuF$nf), ncol=max(PuF$np))
for (sa in 1:puf)
{
Xpuf[PuF$nf[sa], PuF$np[sa]] <-Xmin[(L+fl1):(L+fu)][sa]
}
Xpuc<-matrix(0, nrow=max(PuC$nc), ncol=max(PuC$np))
for (sc in 1:puf)
{
Xpuc[PuC$nc[sc], PuC$np[sc]] <-Xmin[(L+fu1):(L+N)][sc]
```

```
}
#------------------------------------------------------------------
#For constrained nodes
#------------------------------------------------------------------
Q<-NROW(FL) + NROW(PuC)
Xfq<-matrix(0, nrow=max(FL$ne), ncol=max(FL$np))
for (f in 1:fl)
{
Xfq[FL$ne[f], FL$np[f]] <-Xmin[(L+N+1):(L+N+fl)][f]
}
Xcq<-matrix(0, nrow=max(PuC$nc), ncol=max(PuC$np))
for (uc in 1:puf)
{
Xcq[PuC$nc[uc], PuC$np[uc]] <-Xmin[(L+N+fl1):(L+N+Q)][uc]
}
#----------------------------------------------------
#Dynamics (1)
# compute the total value of catches
#------------------------------------------------------------------
Yae<-rowSums(Xca); length(Yae)
#------------------------------------------------------------------
# compute the new value of stock according to:
#------------------------------------------------------------------
Xae<- as.numeric(ST$Stock-Yae + with(ST, r*Stock*(1-Stock/K)))
#--------------------------------------------------------
#Dynamics(2) for frozen tuna
#------------------------------------------------------------------
Xep<-rowSums(Xpf)
lamda<-array(0 ,length(Xep))
for (i in 1: length(Xep))
{
if (Xep[i]>0) lamda[i]<-FL$prix[i]-ST$pr[FL$ne[i]]
}
#------------------------------------------------------------------
# Profit from FF
#------------------------------------------------------------------
Rep<-Xep*lamda
#------------------------------------------------------------------
# Fishing capacity
#------------------------------------------------------------------
FCep<- with(FL, fishing.capacity*(1-neta)+((sigma*lamda*Xep)/prix))
#-----------------------------------------------------------
#Dynamics (3) for canning
#------------------------------------------------------------------
Xcp<-rowSums(Xpc)
lamdac<-array(0 , length(Xcp))
for (i in 1: length(Xcp))
{
if (Xcp[i]>0)  lamdac[i]<-PuC$price[i]
}
#------------------------------------------------------------------
# Profit from CC
#------------------------------------------------------------------
Rcp<-Xcp*lamdac
#------------------------------------------------------------------
# Canning capacity
CCcp<- with(PuC, canning.capacity*(1-neta)+((sigma*lamdac*Xcp)/price))
#------------------------------------------------------------------
```