Game Theory of Fishing: Sustainable Fishing Policies and its Worldwide Effects *

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Abstract

Wild fish stocks are rapidly declining due to overfishing. This affects the balance of the marine ecosystem and the social and economic well-being of the coastal communities. Legislation is introduced on a national and international scale to avoid overfishing. In this paper we present a non-cooperative game-theoretical model, where the different fishing areas defined by the Food and Agriculture Organization of the United Nations (FAO) are the players. Each player tries to optimize their fishing profits, influenced by the fish stock. The fish stock of each player is not only affected by its own fishing behaviour, but also by the behaviour of the player that share currents and fish movement patterns. We designed three variants of the game: (1) each area tries to optimize its profit individually without any restrictions, (2) each area restricts their fishing catch by designing new sustainable policies, and (3) an imitation game in which players mimic behaviour of their successful neighbours. The results of the different variants can be used to understand the effects of fishing policies and to design fishing legislation aimed at boosting fish populations and helping fishing communities to thrive.

Keywords: overfishing, sustainable fishing, fishing policies, policy making, game theory, non-cooperative game, Nash game, imitation

1 Introduction

Fish ranks as one of the most highly traded food commodities and fuels. It is a $362 billion global industry, which provides nutrition and income to a wide range of populations, from poor rural communities to global industry. About 1 billion people rely on fish as their primary source of protein, most of them being in poor areas where other options cannot be found or afforded [1].

The global population is growing; projected to reach 9.3 billion in 2050. The fish stock should grow as well if humans expect to continue to rely on fish as a source of nutrition. Nevertheless, current trends indicate wild fish stocks are expected to decline to 50% of their population by 2050 [27].

Fishing without control can have disastrous effects on the marine ecosystems. This has been known for over a century, but it started being recognized as a problem and defined as overfishing in the early 1970s, when industrial fishing started on a huge scale [46]. In the ensuing decades, technical advances have worsened the impact of overfishing, enabling larger populations of fish to be tracked and caught with minimal effort. Prominent examples include the introduction of diesel boats for fishing in the late 1960s and the appearance of low-light underwater cameras to track fish stocks in the late 1970s [46].

There are three contrasting methods with regards to fishing. (1) Unsustainable fishing is the practice whereby fish are caught faster than they can be replenished. (2) Sustainable fishing in which fish populations continue to grow naturally, and (3) maximum sustainable fishing whereby fish stocks do not have margin for growth but populations remain stagnant [41]. In 1974 the percentage of stocks fished at unsustainable levels was already at 10%. In 2015 this increased to 33.1% and of the remaining 66.9%, 59.7% were fished at maximum sustainable levels [16].

Many countries are concerned about this situation and working to design marine sustainable policies. Moreover, international cooperatives and non-governmental organizations are collaborating to design policies from regional and global perspectives. The Food and Agriculture Organization of the United Nations (FAO) is the international leader, who has drawn up norms, activities and regulations to improve marine sustainability. As part of these regulations, they have defined the major fishing areas (see figure 1) to regulate dif-

*This thesis was prepared in partial fulfilment of the requirements for the Degree of Bachelor of Science in Data Science and Knowledge Engineering, Maastricht University, supervisor: K Staňková and F Thuijsman ferent fishing policies taking into consideration the needs of each area [16]. These areas can be managed through collaboration between governmental and non-governmental institutions. For example, area 27 (north-east Atlantic Ocean) and area 37 (Mediterranean Sea) are managed by FAO and the European Union (EU). There are other organizations that control certain regions or certain species. For instance, the Inter-American Tropical Tuna Commission (IATTC) regulates the tuna stock in east Pacific Ocean and the Convention on the Conservation and Management of Pollock Resources in Central Bering Sea (CCBSP) regulates all fishing activity in the Indian Ocean [16].

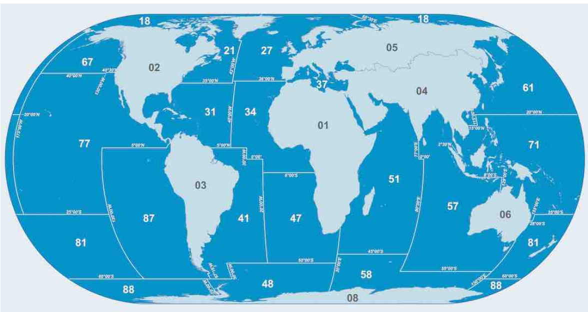

Figure 1: FAO major fishing Areas, from: http://www.fao.org/.

Different types of policies are designed regularly to control fishing and reduce harmful effects. The policies can be classified in three main groups: (1) rules on access to waters to control which vessels have access to which waters and areas, (2) fishing effort controls and fishing quotas to limit fishing capacity and (3) technical measures to regulate gear usage in each area [16, 24].

In many cases, commercial fishing industries try to push these policies back, especially fishing control efforts and fishing quotas, which limit their fishing capacity. When the EU Council meets to set annual quota limits, the commercial fishing industry lobbies for catch limits above scientifically recommended levels, to grant the industry quotas to catch as much fish as possible, with the objective of increasing their profit.

It is very hard to design marine sustainable policies. The marine environment relies on a fragile balance. To this day, we do not fully comprehend the impact of fishing on the marine ecosystem. When designing policies related to fishing, predictions of the impact that these policies will have can be complicated by the unpredictability of our oceans. Calculations on currents and weather patterns can be erratic, with unusual weather events potentially having drastic effects [38].

Both governmental and non-governmental organizations are carrying out research to understand the effects of fishing and fishing policies, predict the fish stock and design more sustainable policies. There is much research done regarding local effects of fishing [1, 12, 13, 31]. Additionally, some researchers are studying the worldwide impact of fishing [3, 37]. For example, the cascade effect, which explains how fishing too much of a specific species leads to a disequilibrium in the marine ecosystem that alters all the wild fish stock [28].

Game-theoretic modelling has made significant contributions to our understanding of the problems of fishery resource management. Game-theory and fishing dates back to 1979, when Munro published a research paper on the potential applications of game theory to fisheries [29]. In it, Munro combined the standard economic model of a fishery with cooperative game theory, showing that if the cooperative management is unconstrained, then, to achieve optimal joint harvest, a player should buy out its impatient partner entirely and manage the resource as a single owner. This was later confirmed by U. Sumaila [44], who developed the computational game-theoretic model. As it is shown in [43], much has been achieved through the use of game theory in analysing fishery management problems, but more needs to be done. Models for the conservation and management of fish need to be fully developed, especially, with respect to developing successful fishing policies.

The biological models underlying such game-theoretic models can be classified into two main categories [33]. First, models of the lumped parameter type, which are a modest interpretation of the real world where all parameters describing the resource are reduced to a two parameter-model, often used because of the simple structure. The model dates back to E. Ricker [34] in discrete time, and to M. Schaefer [36] in continuous time. Second, the cohort models, which explicitly recognise that fish grow with time and suffer natural mortality. The most commonly used model in this class was designed by R. Beverton and s. Holt [5]. In their model, the expected number of individuals in generation t is defined as a function of the number of individuals in the previous generation.

Generally, these games take the form of cooperative and non-cooperative games, with authors usually illustrating the gains to the system through cooperative management [2]. Nevertheless, most of the time the outcomes of the cooperative and non-cooperative game leads to overfishing. For instance, Colin Clark published a game theoretic paper exploring restricted access to public goods resources [8]. This analytical work demonstrated that, for a limited entry system with at least two players, both games result in overfishing.

In this paper we present a non-cooperative game-theoretical model, where we focus on the individual policy design, rather than the cooperation between players. This is based on [39], where K Schüller, K Staňková and F Thuijsman, compare different pollution control scenarios through a non-cooperative game-theoretical model. In our model the fishing areas defined by the FAO (figure 1) are the players, and each player tries to optimize their fishing profits. The game has three variants. A Nash Game where each area tries to optimize its profit individually without any restrictions on fishing behaviour. This makes all areas have the maximum profit at each iteration, finding a Nash equilibrium at each iteration. A Sustainable Policies Game where each area restricts their fishing catch by implementing new sustainable policies that take into consideration the wild fish stock. An Imitation Game where areas imitate the fishing behaviour of those neighbours who have a higher profit.

The addressed research questions are:

1. Is optimizing the current profit without restrictions the most profitable way of fishing in the long run?
2. Is it profitable for an area to have sustainable fishing policies?
3. Is it profitable to imitate the fishing behaviour of neighbours who have higher profit?
4. What is the most profitable fishing behaviour within the given options?

The remainder of the paper is composed as follows: In section 2, we present the model and the basics of the game, we define the players, the functions and the three variants. In section 3, we perform the three case studies, we explain how they were implemented and set. In section 4, we conclude the paper with the discussion of the results and giving an answer to the research questions.

2 Model

In this section we will go over the basics of the game and its variants.

2.1 Game basics

The non-cooperative game-theoretical model can be represented as a directed graph (see figure 2). The nodes are the players of the game, which are the fishing areas defined by the FAO (see figure 1). The edges and its direction represent major currents and fish movement patterns.

Firstly, to define the edges and their transition probabilities, research was done on fish movement patterns and the use of currents by fish [11, 19, 23, 25]. This information was then used to define the edges and to get an initial estimate of the transition probability between nodes. After, the transition matrix was used to calculate the unique stationary distribution of each node [40]. The unique stationary distribution represents the stable percentage of fish population that can be found at every node if no overfishing occurs. Finally, the transition matrix was modified until the unique stationary distribution of each node matched an approximation of the percentage of migratory fish that is at the each corresponding fishing area, based on research on migratory fish [11, 19, 23, 25, 42].

In the model, marine fish, which are fish that live in ocean water [35], are classified as migratory fish and reef fish. The first type includes highly migratory species (HMS), which is a term that has its origins in Article 64 of the United Nations Convention on the Law of the Sea (UNCLOS) [6]. On the other hand, reef fish include fish that do not migrate big distances and therefore stays in the same fishing area all their life. This not only includes fish living in coral reefs, but also coastal fish, which inhabit between the shoreline and the edge of the continental shelf; deep-sea fish, which live in the

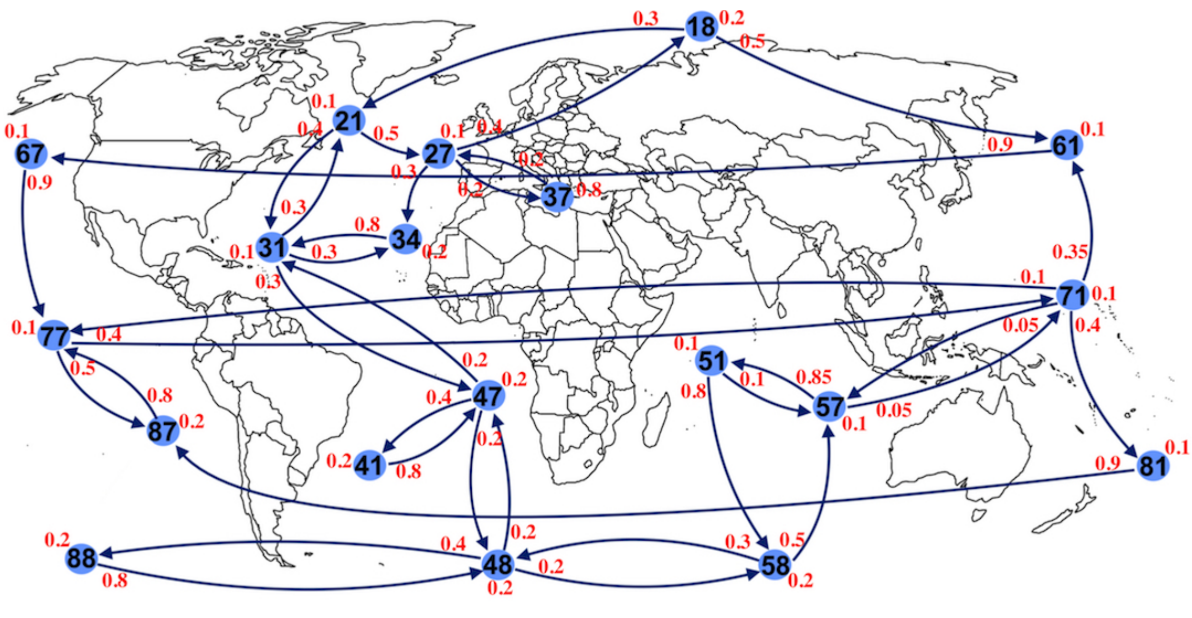

Figure 2: Graph with game players and transition probabilities.

darkness below surface waters, and demersal fish, which reside on the bottom of the sea [10, 35].

Moreover, the model also classifies fish in three different maturation stages: S, M and L. S represents fish that cannot reproduce yet, and which will grow to M. M defines all fish that can reproduce and will grow to L. L represent fish that cannot reproduce because they are too old. It is the last stage before fish dies.

Let us assume that $F = \{S, M, L\}$ is the set of maturation stages and N is the set of fishing areas defined by the FAO, where maturation stages $f \in F$ and area $i \in N$ has a fish stock $x_{if}(t)$ at time $t \in \{0, 1, 2, \dots, T\}$ where $T > 0$. Then

$$x_{if}(t) = y_{if}(t) + z_{if}(t) \tag{1}$$

where $y_{if}(t)$ is the reef fish stock, which depends on fish stock at the previous iteration, fish being fished and fish natural growth, and changes according to the equation

$$y_{if}(t) = y_{if}(t-1)(1 - h_{if}(t))\Bigg(1 + r\Big(1 - \frac{y_{if}(t-1)(1 - h_{if}(t))}{K_{if}}\Big)\Bigg), \tag{2}$$

and $z_{if}(t)$ is the migratory fish stock, which in addition depends on fish flow, and changes according to the equation

$$z_{if}(t) = z_{if}(t-1)(1 - h_{if}(t))\Bigg(1 + r\Big(1 - \frac{z_{if}(t-1)(1 - h_{if}(t))}{K_{if}}\Big)\Bigg) + \sum_{k \in N} z_{kf}(t-1)p_{ki} - \sum_{l \in N} z_{if}(t-1)p_{il} \tag{3}$$

and

$$x_i = \sum_{f \in F} x_{if}. \tag{4}$$

The variable $h_{if}(t)$ is the decision variable. It represents the fishing rate in area i at time t for maturation stage f, where $h_{if}(t) \in [0, 1]$. If $h_{if}(t) = 1$, all fish will be fished, whereas if $h_{if}(t) = 0$, no fish will be fished. In addition, $h_i(t)$ is a vector containing the fishing rates for each maturation stage

$$h_i(t) = \begin{bmatrix} h_{iS}(t) \\ h_{iM}(t) \\ h_{iL}(t) \end{bmatrix}$$

Fish natural growth depends on two variables. The first variable, r, is the growth rate, which includes birth rate and mortality. The variable K_{if} is used to regulate carrying capacity, that is, the natural balance of a population [4]. K_{if} is specific for each maturation stage and K_i is used for the whole population, where

$$K_i = \sum_{f \in F} K_{if} \tag{5}$$

For the fish flow in equation 3, p_{ki} represents the transition probability of inflow coming from area k, and p_{ij} represents the transition probability for the outflow going to area j.

The payoff function of the game is the profit of fishing. Each fishing area i at time t has a profit defined as

$$J_i(h_i(t)) = \sum_{f \in F} j_i(h_{if}(t)) \tag{6}$$

where

$$j_i(h_{if}(t)) = \ln(x_{if}(t-1)h_{if}(t) + 1) - \frac{h_{if}(t)^2}{c} \tag{7}$$

where the first term defines the benefit of fishing and the second term the cost, and where c is a constant that regulates the cost.

The benefit has a logarithmic growth depending on the amount of fish available, $x_{if}(t)$, and the amount of fish being fished, $h_{if}(t)$ [22].

The cost has a quadratic growth with the amount of fish being fished, $h_{if}(t)$, and the constant c regulates this growth. This is based on the expenses of fishing methods, where fishing small rate has a very low cost, meanwhile a large rate has a very high cost [26].

2.2 Game variants

The three variants of the game are non-cooperative differential games where the objective of the players is to maximize their profit $J_i(h_i(t))$.

2.2.1 Nash Game

This variant represents the scenario where fishing companies can fish without restrictions. Therefore, $h_{if}(t)$ is going to be defined by the value that maximizes each player's profit at time t. As a result the collection of all strategies, $h_i^*(t)$ maximises the profit for each area $i \in N$ and forms a Nash equilibrium for time t.

To find the optimal values of $h_i(t)$ that maximizes $J_i(h_i(t))$, the optimal values of $h_{if}(t)$ that maximizes $j_i(h_{if}(t))$ must be found. To do so, the first derivative w.r.t. $h_{if}(t)$ must equal 0

$$\frac{dj_i(h_{if}(t))}{dh_{if}(t)} = \frac{x_{if}(t-1)}{x_{if}(t-1)h_{if}(t) + 1} - \frac{2h_{if}(t)}{c} \tag{8}$$

therefore

$$h_{if}(t) = \begin{cases} 0, & \text{if } x_{if}(t-1) = 0 \\ \frac{-1 + \sqrt{2c(x_{if}(t-1))^2 + 1}}{2x_{if}(t-1)}, & \text{otherwise} \end{cases} \tag{9}$$

because $h_{if}(t)$ cannot be negative.

This can be done because

$$\frac{d^2 j_i(h_{if}(t))}{d(h_{if}(t))^2} = -\frac{(x_{if}(t-1))^2}{(x_{if}(t-1)h_{if}(t) + 1)^2} - \frac{2}{c} \tag{10}$$

which means that $j_i''(h_{if}(t)) < 0$, and therefore $j_i(h_{if}(t))$ is a concave function and for every $h_{if}(t)$ where $j_i'(h_{if}(t)) = 0$, $j_i(h_{if}(t))$ is at a maximum value.

2.2.2 Sustainable Policies Game

In this variant, a policy which restricts the fishing catch is made. A specific quota, $q_{if}(t)$, is designed for every area i, for each maturation stage f and at every time t. We assume that fisheries will then catch the maximum allowed yield, therefore $q_{if}(t) = h_{if}(t)$.

The quota depends on the wild fish stock $x_{if}(t-1)$ and how close it is to reaching the carrying capacity K_{if}

$$q_{if}(t) = \left(\frac{x_{if}(t-1)}{K_{if}}\right)^2. \tag{11}$$

The fishing quota, and therefore the fishing catch, has a quadratic growth with the wild fish stock. When the stock is low, the catch is very low, meanwhile when the stock is high, the catch is very high.

2.2.3 Imitation Game

In this game variant, players have an imitation behaviour. This represents the scenario where countries imitate the fishing practices of those neighbours who have higher profit [18, 32]. The fishing rate is defined as

$$h_{if}(t) = h_{if}(t-1) + \sum_{l \in L_i} \frac{d_{li}}{D_i}\Big(h_{lf}(t-1) - h_{if}(t-1)\Big) \tag{12}$$

where L_i is the set of neighbours of i for whom $d_{li} > 0$, and where d_{li} is defined as

$$d_{li} = J_l(h_l(t-1)) - J_i(h_i(t-1)) \tag{13}$$

and

$$D_i = \sum_{l \in L_i} d_{li} \tag{14}$$

Player i is imitating the average of fishing rate of its neighbours with higher profit, where the player is more influenced by countries that have higher profits than countries with lower profits.

3 Case Studies

For the case studies, a simulation was developed. In this section we will explain the details of the simulation and the settings. Then we will analyse the outcomes of each game variant.

3.1 Simulation

The software was developed using Eclipse IDE for Java Developers, Version Oxigen.2, Release 4.7.2 with execution environment JavaSE-1.8 provided by Eclipse Foundation Inc. (Ottawa, Canada).

The software is a simulation of the model described in section 2. As a result, the simulation works following these steps: (1) fish movement across the fishing areas, (2) fish being fished, and (3) fish reproduction and natural death if applicable.

The software also includes a user interface to select the variant of the game, with an additional option for no fishing.

3.2 Setting case studies

The model includes many variables, constants and parameters with values that must be defined. Many choices had to be made, attempting to be accurate and close to the real marine environment. This was a challenge.

We assume an initial fish stock of 100. 60% of the fish stock is defined as reef fish and 40% as migratory fish. That is based on a comparison of biomasses between the species that are in the UNCLOS list that defines HMS and species that are not in the list [45, 42, 11, 25]. The reef fish is distributed across the fishing areas by researching the marine biomass, the reefs alive and the high concentration of plankton [14, 45]. The migratory fish is distributed across the fishing areas by researching each HMS specie [42, 11, 25]. As a result, the initial fish stock of 100, is distributed as table 1 shows.

The stock is also distributed over the maturation state groups S, M and L as 30%, 50% and 20% respectively.

The reproduction rate, r, has been set at 0.1 [17, 30]. It includes natality and mortality, and the transitions between maturation stages S, L and M, respecting the proportions mentioned above.

To define the carrying capacity, research was carried out regarding the state of the fish stocks, invasive species, top-predators and nutrients in each area [28, 11]. Then K_i was defined as shown in table 1, respecting the proportions mentioned above for the maturation state groups.

The constant c that regulates the cost of fishing is set to 0.4. This is based on research done on all used fishing practices [26] and by testing several constants.

Each iteration of the simulation represents 6 months. This is based on the time species need to migrate [19, 42]. We decided to represent 50 years of time, which means 100 iterations. Therefore T = 100.

Area	Reef	Migratory	Total	K_i
18	5.5	1	6.5	13
21	0.5	1	1.5	12
27	0.5	0.5	1	11
37	0.5	0.5	1	12
31	6	2.5	8.5	17
34	1	1	2	11
47	1	4	5	16
41	0.5	2	2.5	11
88	5	2	7	15
48	5	4	9	20
58	5	3	8	14
51	4	2	6	14
57	8	2	10	16
71	9	2.5	11.5	21
81	2.5	1.5	4	19
87	1.5	3.5	5	18
77	2.5	4.5	7	20
67	0.5	1	1.5	11
61	1.5	1.5	3	12
Total	60	40	100	283

Table 1: Initial fish stock and carrying capacity

For the Imitation Game, the initial fishing rates must be defined. These were approximated by researching the fishing quotas of different countries during the last years [20, 16, 24, 6, 7, 21]. In addition, debates at UN conferences regarding ocean and sea law gave a good insight of the commitments and the fishing practices of each country [15, 9]. These rates were assumed as the following table shows.

Area (i)	$h_{iS}(0)$	$h_{iM}(0)$	$h_{iL}(0)$
18	0%	10%	15%
21	0%	10%	10%
27	0%	5%	5%
37	0%	5%	5%
31	10%	20%	20%
34	10%	10%	10%
47	10%	15%	15%
41	10%	20%	20%
88	10%	10%	10%
48	10%	10%	10%
58	10%	10%	10%
51	20%	30%	30%
57	5%	15%	15%
71	20%	30%	30%
81	0%	5%	5%
87	10%	20%	20%
77	10%	20%	20%
67	0%	10%	10%
61	20%	30%	30%

Table 2: Initial fishing rates.

Four different scenarios are simulated. The first scenario involves no fishing. It was used to test if the simulation behaved as expected. The other three are the game variants mentioned earlier, and the results from each one are going to be shown in the following sections.

To present the results, the same legend is going to represent each fishing area over all the graphs:

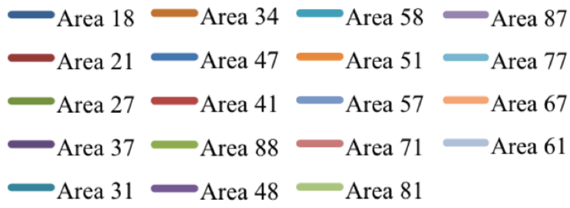

Figure 3: Legend for the graphs.

3.3 Nash Game

In the Nash Game, each area tries to optimize its profit individually without any restrictions. The results of the simulation show what has been happening, is still happening, and will continue to happen, when companies who prioritize short-term profits fish without restrictions.

In figure 4(a) we observe a very high profit at the beginning, followed by a rapid exponential decay. This happens because at the beginning the fish stock is relatively high compared to more advanced iterations, as figure 4(b) shows. It can be appreciated that the wild fish stock has a similar exponential decay. This is caused by the fishing rates which are displayed in figures 4(c)(d)(e).

The high fishing rates at the beginning cause the fish stock to diminish, which causes the profit to fall as well. When the fish stock and the profit are low, fishing rates depreciate as well, until they get stable at low values. This causes both profit and fish stock to stabilise at very low values (see figure 4). As a result, the profit of all areas remains below 0.06 in the final iterations.

3.4 Sustainable Policies Game

In the Sustainable Policies Game, each area chooses a policy that restricts fishing, to conserve and respect the marine ecosystem. As mentioned in section 2.2.2, policy $q_{if}(t)$ equals the fishing rate $h_{if}(t)$ and it depends on the wild fish stock and how close it is to reaching the carrying capacity.

As figure 5(a) shows, some players start with a very high profit, followed by a rapid exponential decline. That is because players with populations close to the carrying capacity are overfished, and their populations are reduced. As figure 5(b) shows, once a population is reduced it stays constant. On the contrary, some players start with a low profit, which grows on the following iterations (see figure 5(a)). This is because some players are in the opposite position, the population is very far from the carrying capacity and the fishing rate is low to allow population growth, shown in figures 5(c)(d)(e). Figure 5(a) also shows that at some point, profit reminds constant, and all players have a profit between 0.15 and 0.28. At this point the wild fish population and all the fishing rates stabilize, fish stock values from different players become closer (see figure 5(b)) and fishing rates for S, M and L stay constant at 0.133, 0.140 and 0.115 respectively.

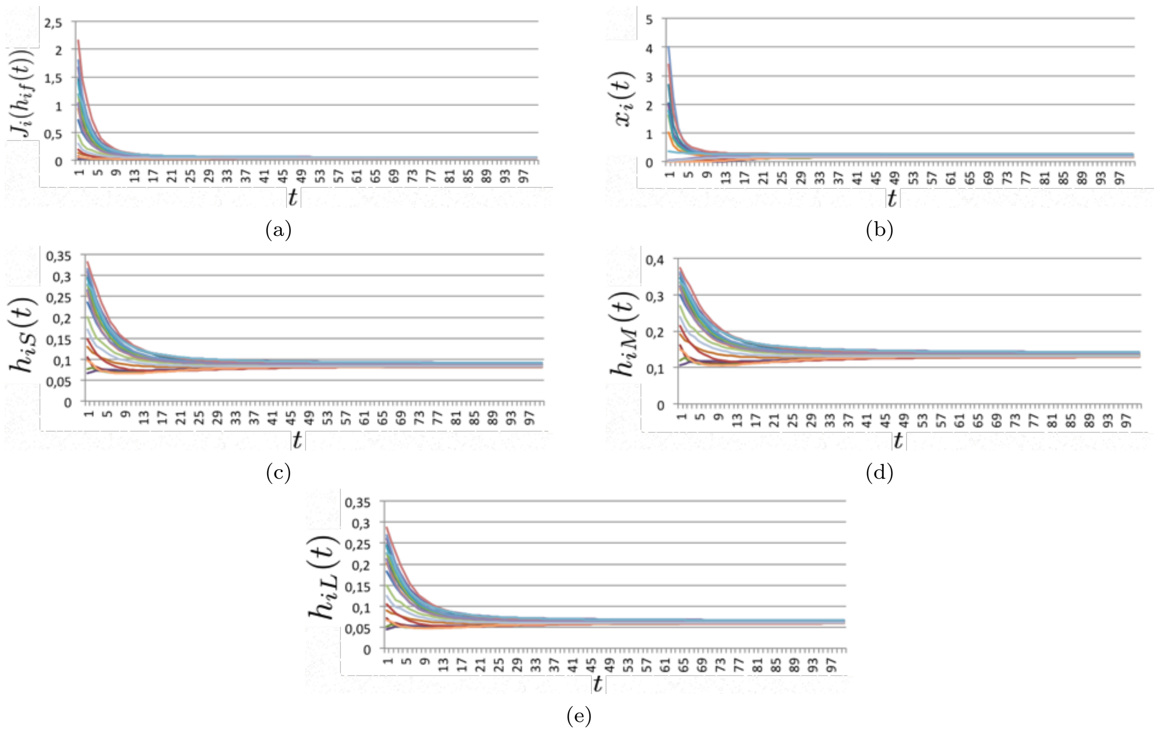

Figure 4: Profit $J_i(h_i(t))$ (a) and wild fish stock $x_i(t)$ (b) behaviour over time, when adapting the fishing rate $h_{if}(t)$ for each maturation stage S, M, L as shown in (c), (d) and (e) respectively, to maximize the profit of each player at each time t.

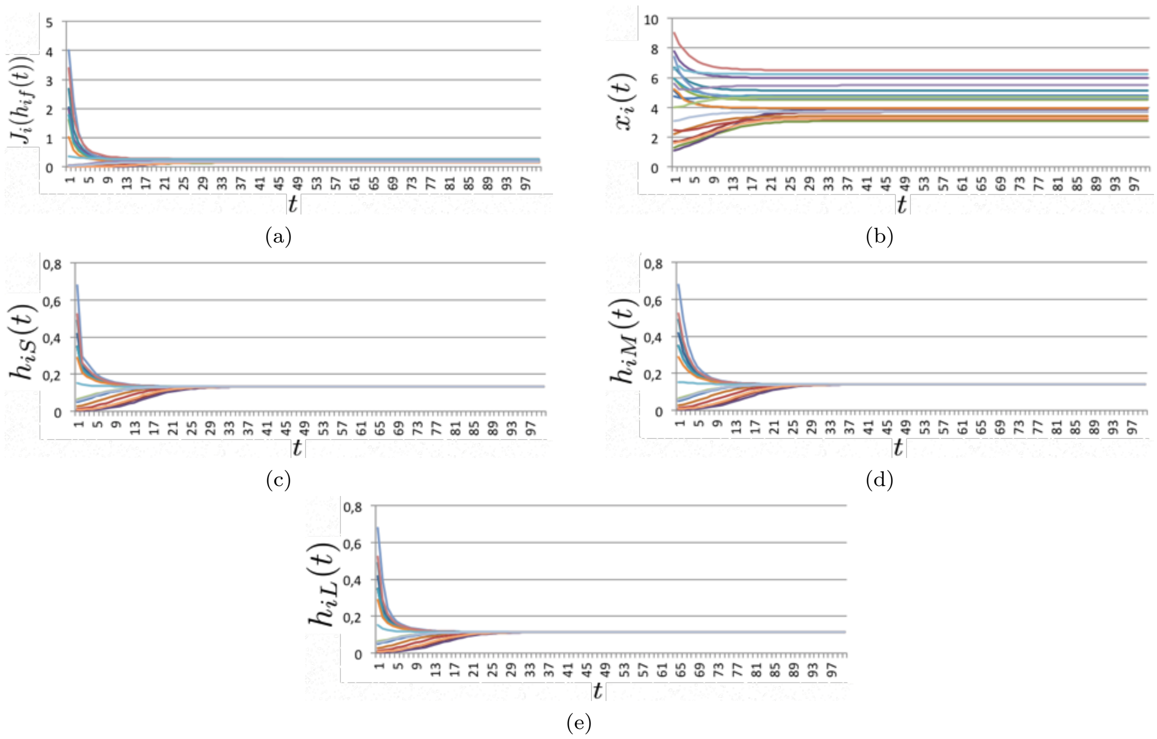

Figure 5: Profit $J_i(h_i(t))$ (a) and wild fish stock $x_i(t)$ (b) behaviour over time, when defining a fishing quota that restricts the fishing rates $h_{if}(t)$ for each maturation stage S, M, L as shown in (c), (d) and (e) respectively.

3.5 Imitation Game

In the Imitation Game, players imitate the fishing rate of neighbours whose profit is higher (see section 2.2.3).

Initially, profit remains low. As figure 6(a) shows, initial iterations show instability, where player's profit behave without a clear pattern, although, most player's profit demonstrates an increase. This is caused by players with low fishing rates increasing them (see figures 6(c)(d)(e)), causing a rise in profit. Meanwhile, players with high fishing rates maintain them, causing profit to decrease as the fishing stock decrease (see figure 6(b)).

After 7 iterations, the fishing rates become stuck in high values and cannot decrease due to all players having high fishing rates. As it was expected, the fishing rates tend to converge because of the imitation behaviour. With only 100 iterations, not all fishing rates converge but we can already see that 13 areas out of the 18 have a fishing rate of 0,1577 for fish of type S, 14 areas have a have a fishing rate of 0,2559 for type M and 16 areas have a have a fishing rate of 0,2559 for type L.

There is a clear trend to converge to the lowest fishing rate within the options defined after the 7th iteration. For most areas, fishing rates converge following a linear or exponential decrease, without big changes between iterations. However, this is not always the case. When only one neighbour has higher profit, the change from one rate to another is big. For instance, in iteration 51, area 48 has a fishing rate of 0.3 for fish of type L. The only neighbour with higher profit is area 47, with a fishing rate of 0.256 for the same type. The new fishing rate for area 48 and for fish type L is 0.256, defined by equation 12. Drastic changes like this happen often between iterations 40 and 70 for fishing type S, M and L, as figures 6(c)(d)(e) show.

The fish stock has a consistent decrease through all the iterations, see figure 6(b). At the last iteration all players have a stock value under 0.000001, caused by the high fishing rates that all players imitated at the beginning.

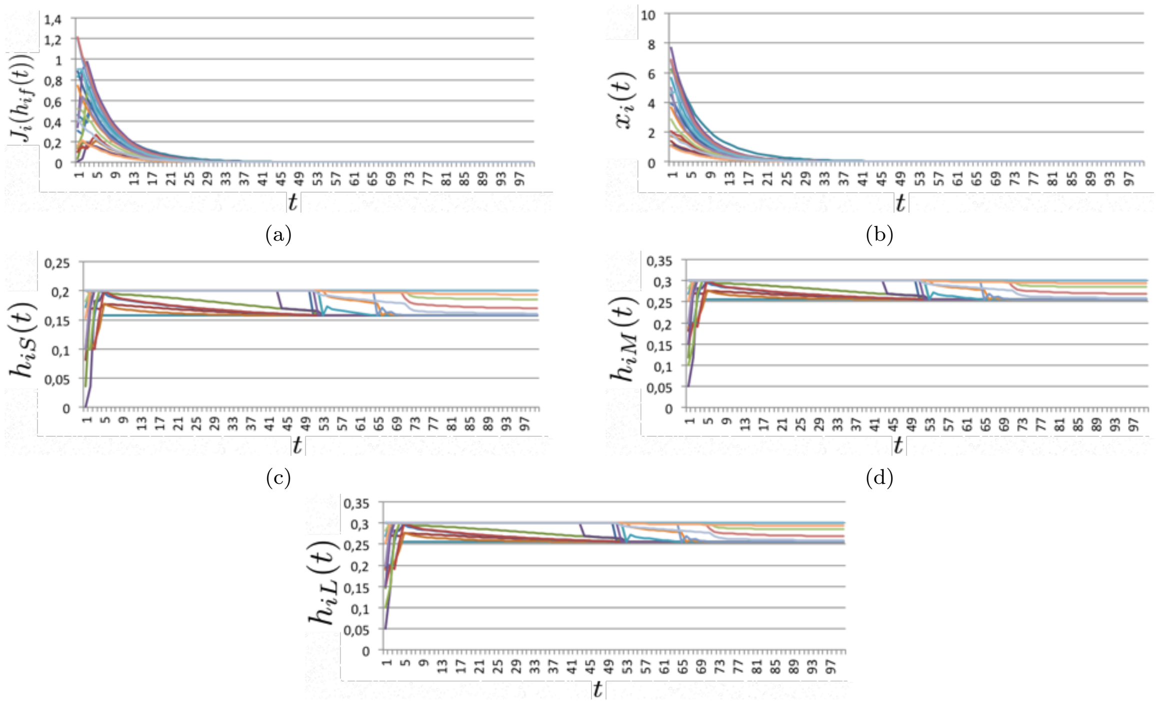

Figure 6: Profit $J_i(h_i(t))$ (a) and wild fish stock $x_i(t)$ (b) behaviour over time, when imitating from neighbours the fishing rates $h_{if}(t)$ for each maturation stage S, M, L as shown in (c), (d) and (e) respectively.

4 Discussion

In this paper we introduce different non-cooperative game-theoretical models in order to provide a starting point for understanding fishing practices and the benefits of fishing policies with regard to wild fish stocks and fishing profit. This is important since then we can find feasible ways of keeping fishing profitable and sustainable.

Our case studies show that fishing without restrictions, prioritizing the short-term maximization of profit, without considering the consequences, will not lead to profitable fishing. Eventually, wild fish stock will decrease leading the fishing activity to have almost no profit, as figure 7(a) shows.

In addition, we demonstrate that, fishing restrictions have a positive effect on the fishing outcomes in the long-term, as figure 7(b) shows. Fishing quotas, which regulate the amount of fish that can be caught, in fact lead to an inflation of the profit. This is especially noticeable in the long run, where the difference between no fishing restrictions and sustainable fishing policies becomes larger. See figure 7(a) and 7(b) for comparison.

Lastly, we prove that imitating the fishing practices of neighbours with higher profits leads to disastrous outcomes in the long term, see figure 7(c). This is because the imitation is based on the highest profit, which means that at the beginning, when all areas still have wild fish in their oceans, the areas with the highest profit are those with high fishing rates. Once the fish stock is low, the areas profiting the most are those with the lowest fishing rates, but as all areas have high fishing rates, rates cannot be decreased much. This also proves that in the long-term, low fishing rates are the most profitable, as all rates converge to the lowest within the high options given after initial iterations.

Overall, we can conclude that the most profitable way of fishing is by setting fishing quotas, in order to better regulate the amount of fish that can be caught.

For future work, we want to improve our model by adding more details. Until now the contamination has not been included. For instance, plastic plays a big role in our oceans, killing many fishes and being a threat to entire species [16], and it is not considered in our model. In addition, we would like to add more variants to the game, to be able to compare more scenarios. For example, an Imitation Game in which player mimic the behaviour of neighbours who have a higher fish stock, instead of prioritizing the profit.

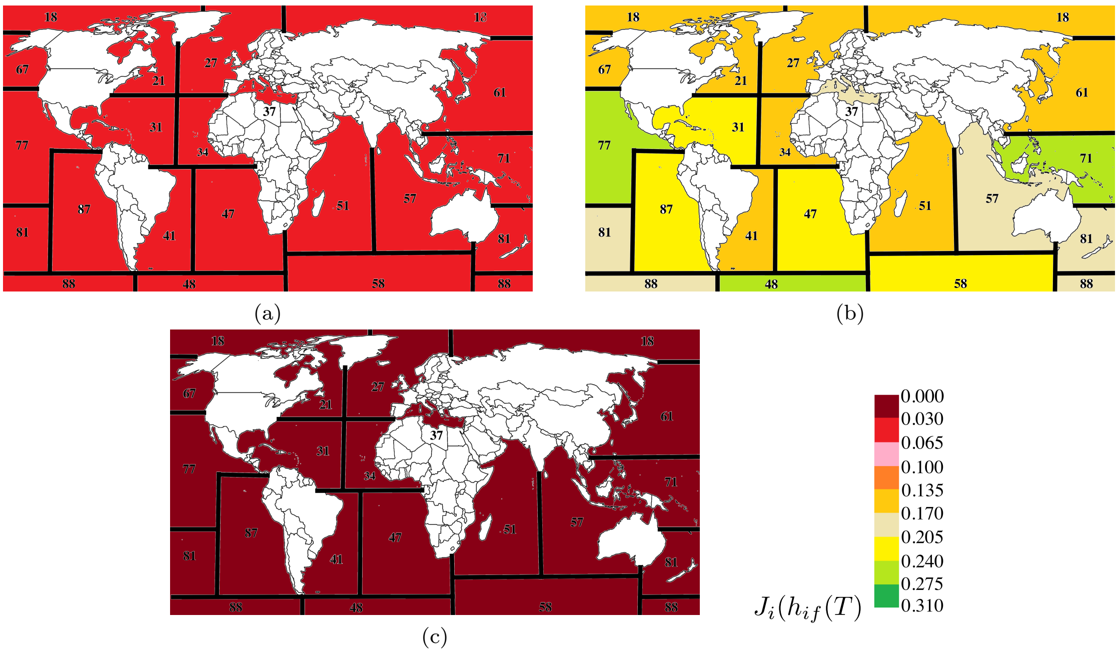

Figure 7: Overview of profit at last iteration for each area and each game variant: (a) Nash Game, (b) Sustainability Policies Game and (c) Imitation Game. Red colour denotes low profit and green colour indicates high profit.

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