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Influence of Tipping Points in the Success of International Fisheries Management: An Experimental Approach

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Abstract —International fisheries are common pool resources which concentrate management difficulties. The migratory nature of fish resources makes it available for a large number of actual and potential harvesters in high seas which are by nature, free of access. This work investigates the role of critical socio-economic tipping points on cooperation during the policy-making process associated with international shared fisheries. We analyze the ability of decision makers to coordinate their decisions to reduce economic rent dissipation and to ensure resource sustainability in a dynamic environment. More specifically, we propose a contextualized computer-based experimental approach to explore how decision makers respond to an endogenously driven catastrophic change in the economic conditions. We use the study case of the East Atlantic bluefin tuna (EABFT) fishery as it has been the archetype of an overfished and mismanaged fishery. We show that the threat of a regime shift, by increasing the likelihood of an economic bankruptcy, fosters more cooperative outcomes and a more precautionary management of the resource. This result is exacerbated when the position of the tipping point which triggers the shift in economic condition is uncertain.

Keywords— Experimental economics; Fisheries management; Common pool resources, Tipping points; International fisheries; Policy making.

1. Introduction

Fishery resources are common-pool resources (CPRs), in which appropriation (catch) of the resource by one fisher creates an external cost for others. In such a context, the incentives to catch more resources and ignore the external costs are rational because a fisher receives benefits for himself without bearing the social costs. Collectively, this rational individual behavior leads to the well-known tragedy of the commons (Gordon 1954; Hardin 1968). Fisheries management has faced difficulties all over the world for the second half of the 20th century and the beginning of this century to address both conservation and economic challenges (Pauly et al., 1998; Worm et al., 2009). Scientists have pointed out the poor governance practices and deficient incentives for conservation (Hilborn et al., 2005).

International fisheries in the high seas are a special case which causes particular management problems. International shared fish stocks are defined as fish stocks not confined to a single national jurisdiction (Economic Exclusive Zone, EEZ), and exploited by more than one State (Munro, 2004). Compared to domestic fisheries, international fisheries are subject to management difficulties mainly due to the need for cooperation between different countries (Munro 1979, Munro et al., 2004, Maguire et al., 2006, McWhinnie 2009, Teh & Sumaila, 2015). Inadequate management has led to overfishing of many economically important fish stocks (Cullis-Suzuki & Pauly, 2010). Highly migratory fish stocks represent the most complex case of international fisheries. The highly migratory nature of such fish resources makes it available for a large number of actual and potential harvesters in high seas which are by nature free of access (White & Costello 2014). Nowadays, the current status of a number of highly migratory stocks (mainly tuna and tuna-like species) is particularly worrying (Juan-Jorda et al., 2011). Since the 1995 United Nations Fish Stocks Agreement, highly migratory species have been managed on a regional basis through Regional Fisheries Management Organizations (RFMOs). The RFMOs are composed of members from both coastal states and distant water fishing nations (DWFNs). Despite the legal obligation to cooperate within a RFMO, the states involved in international fisheries are not required to reach an agreement, or if an agreement is achieved, it is not binding or enforceable (Munro et al., 2004). This means that non-cooperation is the default option, notably in front of the complexity to manage highly migratory species and reach stable agreements.

An example is given by the East Atlantic and Mediterranean stock of bluefin tuna (EABFT), a highly migratory species. Until 2009, the stock has been deemed an archetype of overexploitation and mismanagement (Fromentin et al., 2014). Several countries, both coastal and DWFNs, have contributed to a high level of exploitation driven by the high market value of the tuna on the Japanese market (Fromentin et al., 2014). The decline in the EABFT stock has

raised considerable concerns about its management (ICCAT, 2007, Hurry et al., 2008, ICCAT, 2009). Under the governance of the International Commission for the Conservation of Atlantic Tunas (ICCAT), the fishery has suffered both from its failure to follow the scientific advice and a high level of illegal, unreported and unregulated (IUU) fishing. This situation has occurred since the establishment of the first management regulation based on quotas (Total Allowable Catch, or TAC) in 1999 and lasted until 2009. At this period of time, the objective to reach the Maximum Sustainable Yield (MSY) was far from being achieved. It is only under the threat by environmental Non-Governmental Organizations (NGOs) to propose listing EABFT in Appendix I of CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) which would have prohibited any international trade for this species, that ICCAT established a recovery plan for EABFT since 2009. For the very first time, ICCAT has fully endorsed scientific advice and reached an agreement to considerably reduce the fishing effort and allowable catch as well as implementing some management measures (e.g., size limitations, fishing seasons).

Game theory offers important results about the outcomes of non-cooperative harvest (since the seminal work of Munro 1979, Levhari & Mirman, 1980 and Clark 1980) and the benefits to reach and maintain cooperative agreement in the context of international fisheries (e.g., Brasao et al., 2000, Pintassilgo et al., 2003, 2010, 2015; for a review see Bailey et al., 2010, Hannesson 2011, and Sumaila 2013). However most of the game theory applications in fisheries exclude complex resource dynamics or potential changes in the management framework (Bailey et al., 2010).

As observed in the case of the EABFT fishery, society and public opinion put pressure on RFMOs to address urgently such complex problems, particularly if they perceive a risk of critical threshold to be exceeded. Beyond a critical threshold, management systems can switch swiftly to a high action level with new management frameworks and paradigms (Scheffer et al., 2003). This is the parallel of regime shifts in ecology which are large, abrupt and persistent changes in the structure and function of an ecosystem (Biggs et al., 2012). The point where the shift occurs is called a tipping point. The effects of such tipping points could play an important role in the management of common resources in a high hierarchical and centralized institution, such as the ICCAT or the European Union (EU). The political management systems propose very few incentives to achieve the long term sustainability of stocks (Daw & Gray, 2005). Moreover, stakeholders impacted by ecosystem management may prefer some stability and avoid continuous and costly changes in management recommendations (Armsworth & Roughgarden 2003, Patterson & Resimont 2007, Boettiger et al., 2016). Drastic adjustments to reach stocks sustainability are often taken only once the state of the resources has called society attention (e.g EABFT fishery case in Fromentin et al., 2014).

An empirical method to explore conditions of cooperation in a complex socio-economic system, such as international fisheries, relies on laboratory experiments. Experimental studies on CPRs

have proven to test effectively the impact of specific variables in repeated controlled settings (Ostrom 2006). Our objective is to analyze the ability of decision makers to coordinate their decisions in order to reduce economic rent dissipation and to ensure resource sustainability in a dynamic environment. In the present research work, we assess the cooperation in response to the introduction of endogenous socio-economic tipping points with or without uncertainties. The socio-economic shift considered in this study is a latent and endogenous cost driven by collective actions (aggregated catches). We design our experiment to the case study of the EABFT exploitation following Brasao et al., (2000). Subjects, who are representatives of identical States, are involved in the EABFT fishery management by defining their own catch level (quotas). Our approach can be applied to a variety of CPR situations and collective action problems (Ostrom, 2006, Poteete et al., 2010, Anderies et al., 2011), but our focus in this paper is on ensuring sustainable exploitation of fish stocks. .

Using a dynamic CPR game framework, Lindahl et al., (2016) already studied how the introduction of an ecological tipping point affects the productivity of the resource affects, hence the profitability of CPR users. They showed that a group of users manages a resource more efficiently when confronted to a latent abrupt change. Schill et al., (2015) extended these results by showing that the threshold impact on resource utilization is observed only in situations where the likelihood of the latent shift is highly probable. We extend the experimental work of Lindahl et al., (2016) by testing the effect of the inclusion of a tipping point affecting the economic conditions of the dynamic game in which subjects decisions are based on economic outcomes. We also extend the work of Schill et al., (2015) by analyzing how the position of a latent shift affects resource management instead of analyzing the effects of the occurrence probability.

2. Experimental setting

2.1. Experimental design

Research questions are tested using a modified version of the experimental design of Mason & Philips (1997). This protocol defines a CPR request game (Budescu et al., 1995), in which a few firms harvest a resource in a dynamic context. We adapt their oligopoly model to a situation where the price is exogenously determined (constant price) and include a critical tipping point in the resource level which affects the economic conditions of the game. Following the methodology used in other complex ecological dynamic experiments (Schill et al., 2015, Lindahl et al., 2016), we introduce a non-neutral framework. The task and information given to subjects correspond to a stylized representation of the actual context of the ICCAT decision committee. The subjects are asked to define their harvest levels (quotas) for the East stock of Atlantic

Bluefin tuna, instead of collecting tokens (Harrison and List 2004 for a characterization of experiments). Subjects are only able to communicate through a non-binding pledge process: face to face communication is not allowed. Moreover, to approximate an infinite time horizon supergame, the subjects do not know the number of rounds to be played¹; they only know the maximum duration. However, we make sure to end the experiment early enough to avoid potential end game effects.

We align our experiment onto the model of Hannesson (1997). The yearly CPR biomass dynamics (B_t) is modeled by a logistic growth (1) subject to fishing (Y_t).

$$B_{t+1} = G(B_t) - Y_t \quad (1)$$

With t the year and $G(B_t) = \text{round} \left(B_t \cdot \left[1 + r \cdot \left(1 - \frac{B_t}{K} \right) \right] \right)$.

We assume that the marginal cost of fishing (c) is inversely proportional to the size of the stock at any point in time². The total cost (C) in period t will then be:

$$C(B_t) = \int_{B_t}^{G(B_{t-1})} \frac{c}{x} dx = c \cdot [\ln(G(B_{t-1})) - \ln(B_t)] \quad (2)$$

The fish harvest Y_t caught in period t could be described by $G(B_{t-1}) - B_t$. At a given constant price (p), the total profit (π_t) obtained by all players (i) in period t with a fixed cost (α) associated with an endogenous resource threshold B_{lim} will be:

$$\begin{cases} \pi_t = p \cdot Y_t - C(B_t), & \text{for } B_t \geq B_{lim} \\ \pi_t = p \cdot Y_t - C(B_t) - \alpha \cdot N, & \text{for } B_t < B_{lim} \end{cases} \quad (3)$$

With N the number of participants, and assuming constant return to scale, the individual profit is

$$\pi_{i,t} = p \cdot y_{i,t} - C(B_t) \cdot \frac{y_{i,t}}{Y_t}, \text{ for } B_t > B_{lim} \text{ and } \pi_{i,t} = p \cdot y_{i,t} - C(B_t) \cdot \frac{y_{i,t}}{Y_t} - \alpha, \text{ for } B_t \leq B_{lim}.$$

We introduce a fixed cost related to the resource size beyond the threshold level. This cost is a stylized representation of the critical effect of resource depletion. In the case of the EABFT fishery, this cost represents the effect of a ban on the species commercial exchange. This fixed cost formulation follows the assumptions from public good games with potential catastrophic effects of climate shifts (Milinski et al., 2008, Barret & Danenberg 2012, 2013).

We introduce the resource growth model as a discrete function to our subjects (Figure 1) and the associated profit evolution as depending on the stock and catch levels (Figure 2) for a selection of parameters that fit the context of EABFT (stylized version, Table 1). The minimum resource size allowing for reproduction is 3 units (1 unit is equivalent to 10^4 tons) and the maximum resource size is set to 70 units. The maximum sustainable yield (MSY) is 3 units for a stock size between 28 to 42 units. The profit is maximum, greater than 100 units (1 monetary unit is equivalent to 10^7 €), when both the stock and catch levels are maximum, then it steadily

¹ As in Lindahl et al., (2016), to ensure an unknown time horizon, we varied the end-time between and within groups.

² This cost function implicitly assumes that the cost per unit of fishing effort is constant and the catch per unit of effort is proportional to the size of the exploited stock.

decreases until the stock reaches the lowest values and becomes null at any catch level for a stock size of 10 units. In all treatments, the groups start with a stock size of 52 units and over a number of periods unknown to them, they harvest resource units restricted by an individual capacity constraint of 5 units ($y_{i,t}=[0,1,2,3,4,5]$). Groups are composed of 3 subjects sharing the same characteristics. This design follows the stylized representation from a game theory model of the EABFT fishery (Brasao et al., 2000).

Figure 1: Profit (10^7€) as a function of stock (10^4 tons) and harvest level (10^4 tons).

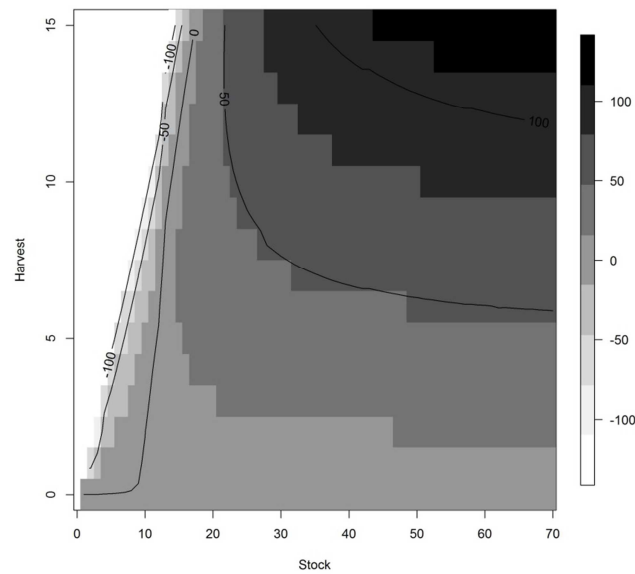


Figure 2: Logistic resource growth (10^4 tons).

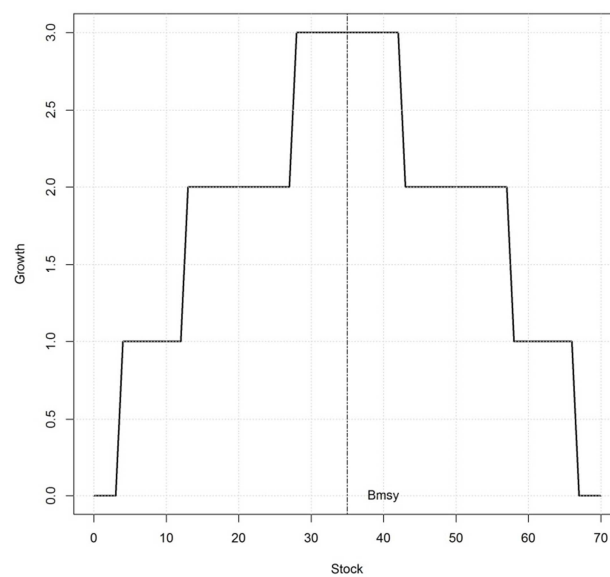


Table 1: Bioeconomic model parameters.

Variable	Description	Value
N	Participant number	3
$y_{\max}$	Maximum harvest [10^4 t]	5
p	Price [10^7 €/10 ⁴ t]	10
r	Growth rate	0.15
K	Carrying capacity [10^4 t]	70
c	Cost parameter [10^7 €/10 ⁴ t]	100
α	Threshold fixed cost [10^7 \$]	30
$B_{\lim}$	Threshold [10^4 t]	20

We introduce three experimental treatments to assess the cooperation in response to the introduction of three kinds of endogenous socio-economic tipping points: i) base case without tipping point; ii) known tipping point and iii) uncertain (localized) tipping point. In all three experimental treatments (T0, T1 and T2 in Table 2), a group of subjects defines a catch harvest for their own EABFT fishery. The only aspects that differ between treatments are the nature of the threshold ($B_{\lim}$). The uncertainty surrounding the latent endogenous shift differs from the risk evaluated by Schill et al., (2015). In our case, the uncertainty focuses on the position of the threshold, and not on its existence. The third treatment (T2) introduces uncertainty around the position of the threshold value $B_{\lim}$ which is drawn within a 40% uncertainty range $[B_{\lim}^{\min}, B_{\lim}^{\max}]$ centered around the value of $B_{\lim 3}$.

Table 2: Experimental design.

	Treatment 0	Treatment 1	Treatment 2
Nature of threshold	No Threshold	$B_{\lim}$	$[B_{\lim}^{\min}, B_{\lim}^{\max}]$
Description	Baseline treatment	Subjects both know that there is a threshold and its position.	Subjects know that there is a threshold but they do not know its position, only a range with equal possibility.
Number of groups	6	6	5
Number of subjects	18	18	15
Number of group observation	2	2	2
Number of experiments	12	12	10

2.2. Experimental procedure

The experiment was conducted at the experimental laboratory of the University of Montpellier (LEEM) with a total of 51 subjects drawn from the undergraduate student population in May 2017. The experiment was conducted through a computer-based approach realized with the oTree software (Chen et al., 2016). Each experimental session lasted a maximum of two hours

³ A 40% was selected to represent a high uncertainty level around the position of $B_{\lim}$.

with two repetitions of the game for the same group of subjects (phases). Participants received a show-up fee of 6 € and the average earnings during the experiments were 2.94 €, paid privately at the end of the experiment.

When the subjects arrived, they signed a consent form and were randomly assigned to a group of 3 subjects with the instructions to read (Appendix A). They were told that each subject represented a country, and that, together with the two other participants of their group, they had access to the stock of the East Atlantic bluefin tuna, a common renewable resource, from which they had to decide the amount of allowable harvest for their fishery at the beginning of each round (each year), before deciding privately in a further step what would be their own harvest decision. Subjects were told that the experiment would end either when the stock is depleted or when the experimenter decides to stop it, but the exact end-period was unknown to them. They began with a capital of 50 monetary units and were paid proportionally to their accumulated profit during the experiment with a rate of 1 unit equal to 0.05€ plus an additional revenue of 0.2€ for correct belief elicitation. Belief elicitation constitutes a guess of the expectation of other subjects' behaviour (harvest level). They received payment for only one phase of the experiment randomly chosen and unknown to them. No direct communication (face to face) between subjects was allowed.

Before the start of the experiment, the subjects were asked to fill out a form to inform their identity and if they were concerned or involved with the subject of the study (Appendix B), and then they were tested for their understanding of the instructions, i.e. resource dynamics and profits (3 questions, Appendix B). Any remaining question was answered by the experimenter. For each round, players received information about the resource state from which a profit table is derived and updated for every round (Appendix C). They were also informed about the percentage variation of the biomass for the next year through a variation table depending on the harvest level of the group (Appendix C). Furthermore, the mean resource level at MSY (35 units) was also indicated with the resource status and defined as a non-binding objective for the group. This information creates a collective reference point in order to facilitate the understanding of the long term sustainable resource level maximizing the growth of the resource. Therefore, optimizing the use of the resource can focus on the mere level ensuring maximum profits. This information is necessary to concentrate the problem on the resource sharing issue, and not on the optimization of a non-linear dynamic system which proved to be a complex problem (Moxnes, 1998 and Hey et al., 2009).

On top of deciding their harvest level, the subjects had to guess the sum of harvest units they expected the other players would harvest in each period from 0 to 10 units. Belief elicitation was incentivized with a payoff of 0.2 € for good prediction and allowed examining the source of deviations from theoretical predictions. Thereafter, participants pledged an amount of catch

they would harvest individually. It was common knowledge that these declarations were non-binding but would be communicated to the group. After these declarations were revealed, the participants chose simultaneously their actual harvest level for the round (year). At the end of the round, the participants were then informed about everyone's decisions for the round and they were given their cumulated profit and the track records of the total catch, profit and own decision during the game. They also had access to a projection of the future resource status assuming a constant harvest level scenario defined at the current harvest level (Appendix D). At the end of the experiment, participants were informed about their cumulated profit. They were also asked to indicate, on a five-point Likert scale, to what extent they understood the resource dynamics and the cooperation level of their group during the experiment.

2.3. Formulating hypothesis

To formulate the research hypotheses, we rely on the analysis of an indefinite time horizon supergame made by Hannesson (1997). The subjects know that the game will end at some point but not when. At every round of the game, each subject i in the group has an individual perception about whether or not the game would last another round (sort of a discount factor), which we denote δ_i (Fudenberg and Tirole 1998). The implication of these subjective probabilities defines the equilibrium conditions of the game.

During the experiment, participants receive updates on the stock level B_t and on their available profit at the beginning of each period. They also know if someone deviates from its proposition and if a participant behaves as a selfish agent. Thereby, each participant conditions his strategy on past and current resource and profit levels. On the basis of this information, each participant plays a Markov strategy (Maskin and Tirole 2001). Because players are symmetric (same cost functions), we only consider equal sharing equilibria (equal share of the resource) in which each subject gets $\frac{1}{N}$ of the total profits of each period.

Cooperative strategy could be sustained by a trigger strategy in the game. Considering the case without tipping point, if one of the participants deviates from the optimal solution, she/he would gain more in the current period and would then be punished afterwards. Other players would retaliate by fishing down the stock in the following periods until further depletion becomes unprofitable. Such a scenario results in resource depletion until the marginal cost of fish caught (c) is equal to the marginal revenue, i.e. the fish price (p , Eq. 3). The size of the stock resulting from such a strategy is then:

$$B_{tr} = \frac{c}{p} \quad (4)$$

Otherwise, the optimal solution could be sustained as a Markov perfect strategy if the defection is not profitable. The net present value of the cooperative strategy, NPV_c , for infinite horizon is:

$$NPV_c = \frac{\pi_0}{N} + \frac{\pi_c}{N} \cdot \frac{\delta}{1-\delta} \quad (5)$$

With an initial stock of 52 units (10^4 tons), the optimal outcome is obtained by harvesting the stock until the optimal level, B_{opt} is reached in the first period, each subject gaining $\frac{\pi_0}{N}$. In each subsequent period, the group harvests the sustainable yields $[G(B_t)]$ until the stock reaches its optimal size B_{opt} and each subject obtains $\frac{\pi_c}{N}$.

The net present value (NPV_d) of the non-cooperative strategy is defined for a participant who deviates from the cooperative solution and which is then punished by all other participants playing non-cooperatively afterwards and forever⁴.

$$NPV_{dev} = \frac{\pi_0}{N} + \frac{\pi_c}{N} \cdot \delta + \pi_d \cdot \delta + \frac{\pi_p}{N} \cdot \delta^2 + \frac{\pi_{tr}}{N} \cdot \frac{\delta^3}{1-\delta} \quad (6)$$

With $\pi_{opt} = p \cdot (G(B_{opt}) - B_{opt}) - c \cdot [\ln(G(B_{opt})) - \ln(B_{opt})]$;

$\pi_d = p \cdot (B_{opt} - (B_d)) - c \cdot [\ln(B_{opt}) - \ln(B_d)]$;

$\pi_p = p \cdot (G(B_d) - B_{tr}) - c \cdot [\ln(G(B_d)) - \ln(B_{tr})]$ and

$\pi_{tr} = p \cdot (G(B_{tr}) - B_{tr}) - c \cdot [\ln(G(B_{tr})) - \ln(B_{tr})]$.

In the first two periods, the defector gets the same profit as in the cooperative solution, as all other participants play cooperatively, and in addition the defector gets the profit of driving the stock down unilaterally to B_d (and get π_d). In the third and all later periods, he will be punished by all other agents playing non-cooperatively, driving the stock down to the level B_{tr} . (10 units) and gets the profit $\frac{\pi_p}{N}$. Then, the defector gets only the profit obtained in the non-cooperative solution $\frac{\pi_{tr}}{N}$.

The trigger strategy forms a subgame perfect equilibrium, if the defection is not profitable, $NPV_c > NPV_d$ ⁵, which gives the condition:

$$\pi_c > \frac{1-\delta}{\delta} \cdot N \cdot \pi_d + (1-\delta) \cdot \pi_p + \delta \cdot \pi_{tr} \quad (7)$$

⁴ Punishment strategies may last a finite number of periods. As we are interested in the effects of increasing the fishing through the introduction of a tipping point we keep simple strategies.

⁵ A more general way to describe the conditions for cooperation can be defined following the logic of Mason & Phillips (1997). Consider a cooperative harvest function, $y^c(B_t)$, a trigger strategy can be described by playing cooperatively $y^c(B_t)$, as long as no one has defected. If one of the participants deviates from the optimal solution, then others will punish him by fishing down the stock with harvest $y^d(B_t)$, afterwards and forever. Using the cooperative harvest and resulting stock path, we may derive the net present value for the player under cooperation $NPV^c(B_t)$. Similarly, we may calculate the non-cooperative value function, $NPV^d(B_t)$. The trigger strategy forms a subgame perfect equilibrium if the defection is not profitable, irrespective of the current state.

$$NPV^c(B_t) > \pi^d(y^d(B_t)) + \delta \cdot NPV^d(B_t)$$

As δ tends to 1 (i.e. the discount rate tends to 0), defection will never be profitable (by definition $\pi_c > \pi_{tr}$). In other words, the loss from punishment will always outweigh the gains from defecting. As δ becomes inferior to 1, the temporary gains from defecting may outweigh the long term profit of playing cooperatively. Moreover, the temptation of defecting decreases with higher fishing costs. A higher cost of fishing (c) increases the likelihood of a cooperative solution (the demonstration can be found in Hanneson, 1997). However, the introduction of a fixed cost triggered by fishing down the stock below the threshold B_{lim} changes the size of the stock resulting from non-cooperative strategy B_{tr} from a level where further depletion becomes unprofitable (since the marginal cost of fish caught is equal to the price) to the level of the threshold B_{lim} which is by definition superior to B_{tr} ($B_{tr}=c/p$). Consequently, the gains from the cooperative solution relatively to the non-cooperative solution become smaller and for low discount values the cooperative and non-cooperative solutions coalesce and lead to our first hypothesis.

Hypothesis 1 We expect less cooperation when a tipping point is introduced⁶ (T1 and T2).

We analyze the level of cooperation through the stock size left after exploitation. A stock size below the optimal level (B_{opt}) indicates an over-exploitation driven by non-cooperative behaviours. We also introduce a proxy of non-cooperative behaviours, the ratio between the harvest decision ($y_{i,t}$) and the myopic harvest strategy $y^e(B)$, determined as a function of the stock size (see Appendix G for a description of the myopic harvest strategy $y^e(B)$). A value equal to 1 indicates that the participant chose to play as a selfish harvester maximizing his current payoff⁷, whereas a value inferior to 1 indicates that the participant intended to cooperate. Now turn to the case where the position of the threshold is uncertain. Considering risk-neutral players, the problem facing by each subject is now:

$$\pi_{i,t} = \begin{cases} p \cdot y_{i,t} - C(B_t) \cdot \frac{y_{i,t}}{Y_t}, & \text{for } B_t > B_{lim}^{max} \\ p \cdot y_{i,t} - C(B_t) \cdot \frac{y_{i,t}}{Y_t} - \alpha \cdot \left[1 - \left(\frac{B_t - B_{lim}^{min}}{B_{lim}^{max} - B_{lim}^{min}} \right) \right], & \text{for } B_t \in [B_{lim}^{min}, B_{lim}^{max}] \\ p \cdot y_{i,t} - C(B_t) \cdot \frac{y_{i,t}}{Y_t} - \alpha, & \text{for } B_t < B_{lim}^{min} \end{cases} \quad (8)$$

In face of ambiguous situation, the size of the stock resulting from non-cooperative strategy (where further depletion becomes unprofitable) becomes superior to B_{lim} when an uncertain tipping point is introduced (T2). Following the same rationale as for defining hypothesis 1, the

⁶ For our parameterization we calculate in Appendix F, the relationship between the critical value of the discount rate (δ) and the number of participants (N) compatible with a self-enforcing cooperative solution (Equation 7).

⁷ Myopic behavior constitutes a focal point distinguishable as the symmetric harvest decision which maximizes the current payoff (diagonal in the payoff table in Appendix C).

gains from the cooperative solution relatively to the non-cooperative solution become smaller and lead to our second hypothesis.

Hypothesis 2 We expect less cooperation in T2 than in the known threshold position treatment T1.

2.4. Statistical Analysis

We first compare means and proportions across the treatments of main variables (Table 3). We used respectively the non-parametric Kruskal-Wallis and a Pearson's chi square tests for comparisons of means and proportions (Table 4). All reported p-values are two-sided and we only consider the first 15 rounds of the game for our analysis.

Then, we analyze pledges and players' beliefs by classifying subjects according to their ability during the experiment to predict other player's behavior (belief elicitation) and their intentions to follow or not the pre-agreements during the game (i.e. pledges before harvest decisions). We define 3 types of subjects based on their mean prediction, beliefs errors: optimistic (belief < others harvest), realistic (belief = others harvest) and pessimistic (belief > others harvest). We also define 3 types of subject's behavior according to their mean responses (harvest decisions) to others' pledge: altruistic (harvest decision < pledges/ (N-1)), consensual (harvest decision = pledges/ (N-1)) and free-rider (harvest decision > pledges/ (N-1)). The subject type (Table 3) is a classification of subjects based on their highest frequency belief errors (optimistic, realistic or pessimistic) and intended harvest behaviors (free-rider, consensual or altruistic).

Finally, the experimental data, are analyzed with a population average generalized estimating equation model (GEE, developed by Zeger & Liang 1986) with the "geepack" library (Halekoh et al., 2006) available in the programming language R (R Core Team, 2016). The GEE model approach is an extension of the Generalized Linear Model (GLM). It provides a semi-parametric approach to longitudinal data analysis. Longitudinal data refers to non-independent variables derived from repeated measurements. In our experience, we measure repeated decisions of participants which are correlated from one period to another. The GEE model allows an analysis of the average response of a group, i.e. the average probability of making a myopic harvest decision given the changes in experimental conditions, accounting for within-player non-independence of observations. The decision of a participant in year $t + 1$ is linked to his decision in year t , thus violating the hypothesis of independence of the observations formulated in the classical regression methods. For controlling group dependences which occurs through resource stock and social effects, we performed the same GEE analysis on the average group ratio of harvest decisions over myopic strategies. In this model, we consider that a correlation of the mean group in period $t + 1$ is linked to the decisions in period t .

The modeling approach also requires a correlation structure, although this methodology is robust to a poor specification of the correlation structure (Diggle et al., 2002). Our dataset consists of a series of successive catch decisions made by a participant during each phase. The grouping variable of the observations is therefore based on each experiment. Since the data is temporally organized, a self-regressive correlation structure (AR-1) is selected. Model selection is performed by testing combinations of the covariables (R package MuMIn, Barton, 2014) based on Pan's quasi-likelihood information criterion (QIC, Pan, 2001) and individual Wald test. We focus our analysis on the ratio of the harvest decision and the myopic harvest strategy. This variable, which is a proportion that can be modeled by a binomial distribution with a logit link function, specifying a variance of the form: $var(Y_{i,t}) = p_{i,t}(1-p_{i,t})$, with $Y_{i,t} = \frac{y_{i,t}}{y^e(B)}$ corresponding to the response variable for participant i during period t and $p_{i,t}$ the probability of the expected value of $Y_{i,t}$ ($E[Y_{i,t}] = p_{i,t}$). As for the logistic regressions, we tested for specification errors, goodness-of-fit, multicollinearity as well as for influential observations.

Table 3: Description of variables used for analysis.

Variable	Value range	Description
Harvest as a fraction of myopic strategy	R^+	Individual harvest decision as a fraction of the myopic strategy by period.
Crossing threshold	$0 \vee 1$	Group crosses the threshold within 15 rounds.
Belief error (error in other harvests level belief)	$[-10,10]$	Difference between beliefs and the sum of harvest by other participants by period.
Intended behavior	$[-5,5]$	Difference between harvest and symmetric harvest beliefs of other participants by period (pledges/(N-1)).
Subject type	[optimistic, realistic, pessimistic, free-rider, consensual, altruistic]	Classification of subjects based on their highest frequency belief errors (optimistic: belief < other harvest, realistic: belief = other harvest and pessimistic: belief > other harvest) and intended harvest behaviors (free-rider: harvest > pledges / (N-1), consensual: harvest = pledges / (N-1) and altruistic: harvest < pledges / (N-1)).
Knowledge index †	[1,5]	Perceived understanding about the resource dynamic..
Score test †	[0,3]	Individual score to the understanding test.
† Self-reported variable, obtained from pre and post-experimental survey (see Appendix B).		

3. Results

3.1. Overall exploitation management decision patterns

We found significant differences between treatments (Table 4). First, the threshold treatment groups (T1, T2) cooperate more on average, participants use significantly less myopic strategies and groups deplete significantly less the resource (higher average stock). Furthermore, the groups playing in the threshold treatments which exceed the threshold, experience an important cost that diminishes drastically their profit. We therefore observe a lower average in profit with a high variability between groups. Furthermore, we observe an effect of uncertainty around the threshold (T2). Groups who experience threshold uncertainty cooperate more if we consider the

ratio of harvest decision on the myopic strategy and the mean resource level. However, the proportion of groups exceeding the threshold is higher than in the first treatment (T1)⁸.

Table 4: Comparison of proportions and averages across treatments.

	Treatment 0	Treatment 1	Treatment 2	p (Kruskal-Wallis test, χ^2 or Fisher's exact test) [†]
Average group harvest as a fraction of myopic strategy	0.81 (0.54)	0.65 (0.80)	0.53 (0.72)	0.074*
Average group stock level	20.20 (15.3)	27.80 (13.9)	30.30 (15.8)	0.013*
Proportion of group exceeding the threshold	–	0.58	0.70	0.68
Average earning [€] ^χ	4.40 (4.62)	2.17 (4.29)	2.15 (3.82)	0.11
Average group profit	10.31 (22.70)	2.90 (29.30)	0.40 (31.54)	0.047*
Average group harvest	1.49 (1.80)	1.54 (1.57)	1.42 (1.60)	0.24
Average group pledge	1.02 (1.48)	1.20 (1.50)	1.26 (1.50)	0.32
Average group belief error	-0.87 (3.00)	-0.66 (2.90)	-0.51 (2.80)	0.53
Average group intended behavior	0.46 (1.70)	0.34 (1.61)	0.16 (1.75)	0.27
Average post-experimental survey understanding index ^{†,ν}	3.90 (1.24)	3.90 (1.10)	4.30 (0.87)	0.27
Average pre- experimental test understanding index ^{†,Γ}	2.00 (1.00)	1.39 (1.00)	1.60 (1.20)	0.04*

Note: Standard errors in brackets.

*Indicates significance $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$.

[†] Self-reported variable, obtained from pre and post-experimental survey (Appendix B).

[†] Kruskal-Wallis test is used to compare means across treatments and χ^2 or Fisher's exact test (depending on the case frequencies) used to compare proportions across treatments.

^χ Average earnings (from profits and belief elicitation) doesn't include participation fees.

^ν Average understanding index is the answer from the post-experimental survey on a five-point Likert scale.

^Γ Average pre- experimental test understanding index is the score from the 3 pre-experimental questions (Appendix B). A score of 3 indicates a perfect understanding, while a score of 0 a very weak comprehension of the experiment dynamic mechanisms before clarification by the experimenter.

The overall catch decreasing pattern until the steady state stock size corresponding to the trigger strategy was found similar between groups in the treatment without a threshold (T0, Figure 3). All groups in the treatment T0 followed the trigger strategy and exploited the resource until the stationary non-cooperative equilibrium (10 units). Only 3 groups over 34 managed to maintain the biomass level close to the long term optimal level (40 units), for which the regeneration rate was the highest while the harvesting cost was low. They all belong to the treatments groups (one in T1 and two in T2).

In contrast with our theoretical prediction, the majority of groups (7) in the certain thresholds treatments (T1) harvest beyond the threshold. None of these groups is able to reverse the negative trend of stock depletion despite the high penalty cost. We observe the same pattern in the uncertain threshold treatment (T2) with 7 cases of exploitation falling beyond the threshold

⁸ We also test the potential effect of playing 2 games (phases) sequentially. We did not find any significant difference between phases using the Mann-Whitney-Wilcoxon test on group averages (Appendix H).

level. Moreover, despite the high cost related to the full depletion of stocks, two groups have intentionally exhausted the resource to end the experiment.

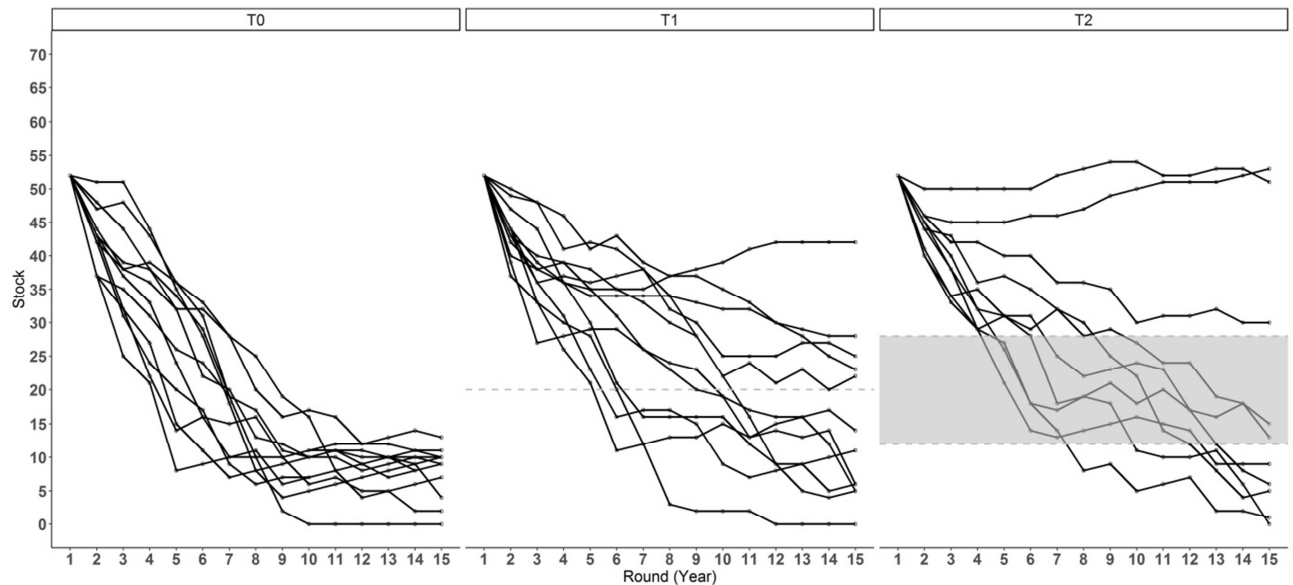


Figure 3: Time series of resource stock size (biomass in units) by treatments (T0, T1 and T2).

The grey dashed line corresponds to the threshold B_{lim} in T1 and the shaded area to the uncertainty range around the potential value of B_{lim} in T2.

We observe a lower proportion of myopic strategies in the threshold treatments (T1 and T2) which contradict the theoretical predictions (Figure 4). Moreover, we notice more cooperation (lower proportion of myopic strategies) in the uncertain threshold treatment than in other experimental conditions (Table 3). We also clearly discern a time pattern linked with the scarcity of the resource regardless of the treatment.

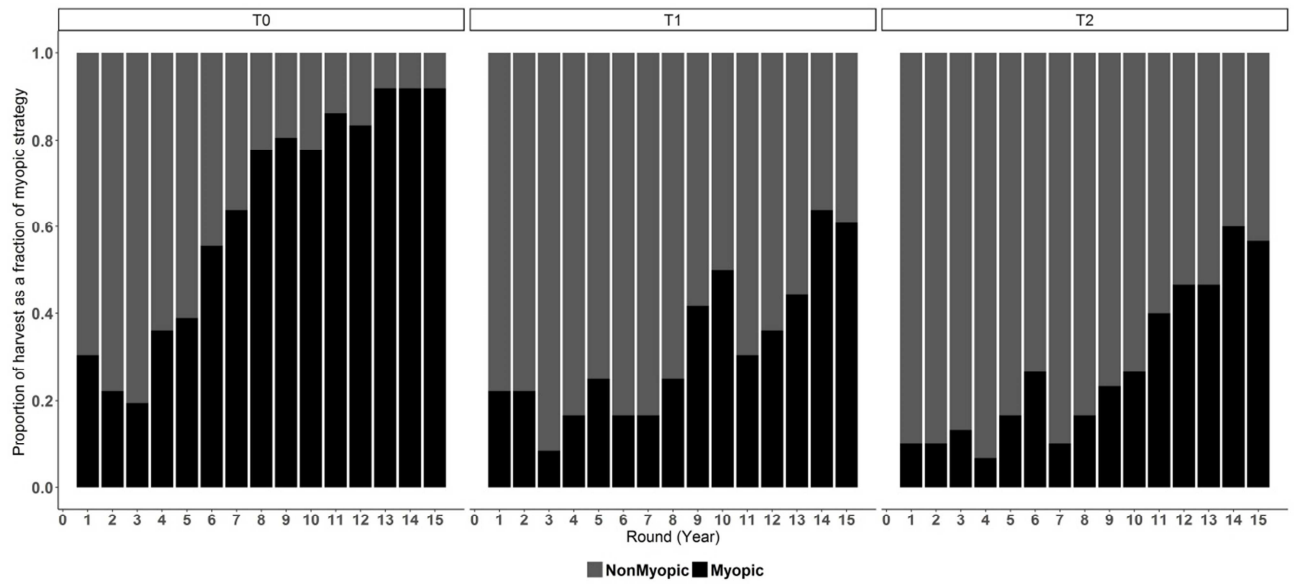
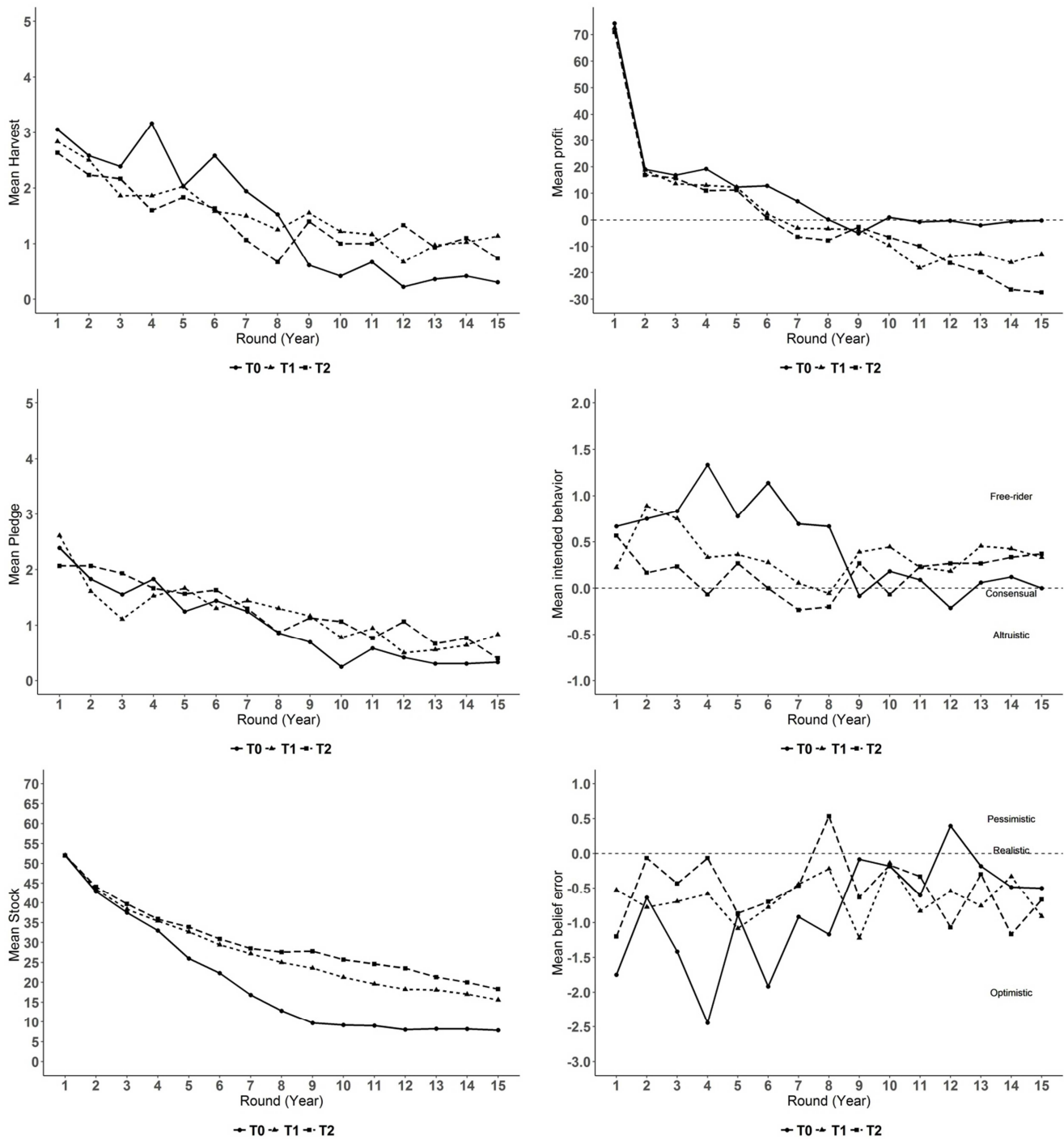


Figure 4: Proportion of harvest as a fraction of myopic strategy over times by treatments (T0, T1 and T2) summarized into a categorical variable: ‘Myopic’ if the ratio of the harvest choice over the myopic strategy is superior or equal to 1 and ‘NonMyopic’ if the ratio is inferior to 1.

To go further into the analysis of individual strategies, we show that the more intensive harvest pattern (Myopic behavior, Figure 5) in T0 during the first rounds (0 to 8) conduct the stock to B_{tr} (10 units) and zero profits as a result of the application of the trigger strategy. Participants’ announcements (pledges) and harvest decisions are helpful to understand the start of the trigger strategy (punishment of free-riders by overexploiting the stock until further depletion becomes unprofitable). During the first rounds in which we observe the highest mean harvest decision, participant’s pledges are strictly inferior to harvests conducting participants into intended free-riding behavior (intended behavior >0). On the other hand, mean participants’ beliefs are too optimistic: they expect other players to harvest less following their announcements (belief error <0). Threshold treatments exhibit the same pattern with a less marked trend in free-riding intended behaviors and prediction of other participants’ harvests. The classification into distinct subject types summarizes this information by showing the highest proportion of free-riders and optimistic participants in the experiments (Figure 6). Likewise, this information highlights the high frequency of consensual participant which strengthens the theoretical hypothesis that participants use consensual punishment strategy.



428 **Figure 5:** Time series of mean harvest and pledge decisions, and mean resulting resource stock
 429 size, profit, intended behavior and belief error by treatments (T0, T1 and T2).
 430

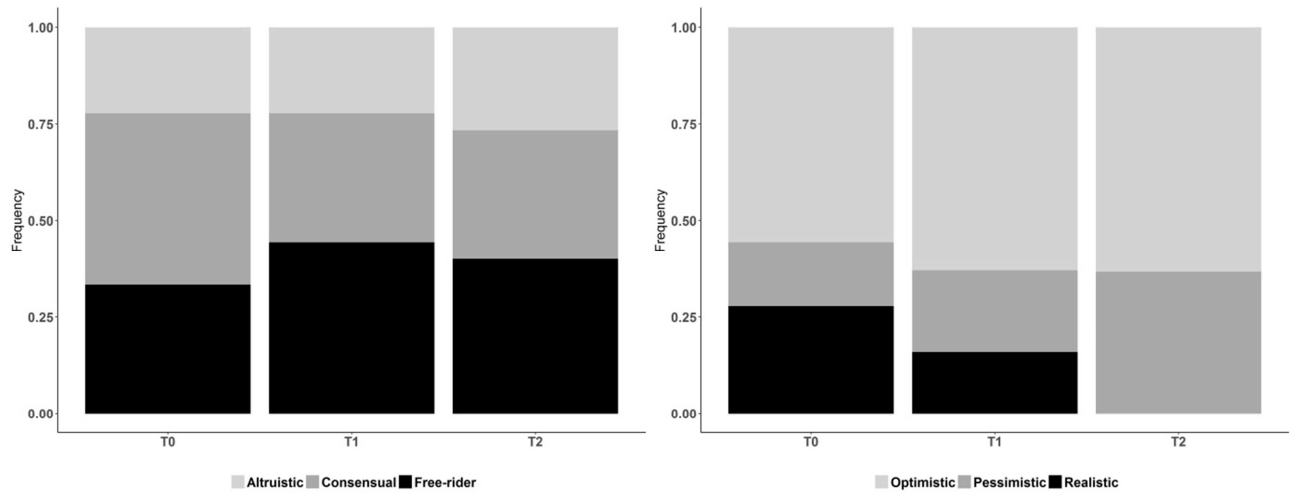


Figure 6: Frequency of subject types for the whole experiments and by treatments (T0, T1 and T2). Classification of subjects based on their highest frequency belief errors (optimistic: belief < other harvest, realistic: belief = other harvest and pessimistic: belief > other harvest) and intended harvest behaviors (free-rider: harvest > pledges / (N-1), consensual: harvest = pledges / (N-1) and altruistic: harvest < pledges / (N-1)).

3.2. Exploring predictors for cooperation

The selected GEE regression model (Table 5)⁹ reveals that groups playing the threshold treatment (T1 and T2, $p < 0.001$) are more cooperative. On average, the odds, ceteris paribus, of behaving myopically in the no threshold treatment (T0) over the odds of behaving myopically in the threshold treatments (T1 or T2) is about 2.56 (inverse of the odds in Table 5). In term of percentage of variation, the odds of behaving myopically among the no threshold treatment groups is around 156% higher than groups in the threshold treatment. The threat to cross the threshold enhances cooperation by mitigating selfish behaviors.

We can also identify the effect of the resource scarcity on subjects mean harvest decisions. When subjects start experiencing scarcity, they significantly tend to select myopic decisions (biomass level effect, $p < 0.001$). Participants are stuck in short-sighted competitive behaviors. In all treatments, the proportion of myopic decisions increases by approximately a factor 3 to 4 between the first and the last rounds of the experiment (Figure 4). This observation is confirmed by the average continuous decreasing trend of biomass throughout time (Figure 3).

The subject type is also an important explanatory variable which is defined by the ability of participants during the experiment to predict other players' behaviors (belief error) and their intentions to follow or not the agreement contracted during the game (intended behavior, Table

⁹ We also compared GEE models to random group effect generalized linear models (GLMM with package 'lme4' Bates et al., 2015 in R, Appendix I). The results are qualitatively similar with a higher magnitude of treatment and free-rider participant coefficients.

3). The presence of free-riding participants significantly affects the mean odds of choosing myopic strategies. Those participants who deliberately deviate from the other pledges (catch > pledge/2) selected on average more myopic strategies than other players and lead to stock depletion with the implementation of the punishment (trigger) strategy. Furthermore, the significant positive coefficient of realistic and consensual participants confirms our previous analysis that participants use consensually a punishment strategy.

Table 5: Generalized Estimating Equation regression for the average probability of making a myopic harvest decision.

Binomial regression models	GEE regression Best model	GEE regression Best model
	Harvest as fraction of myopic strategy	Mean group harvest as fraction of myopic strategy
Intercept	1.55*** (0.22)	1.93 *** (0.30)
Treatment 1	-0.91*** (0.16)	-0.75** (0.24)
Treatment 2	-0.97*** (0.17)	-1.01** (0.29)
Biomass	-0.04*** (0.004)	-0.03*** (0.008)
Player class Consensual†	0.18 (0.20)	-
Player class Free-rider	0.73*** (0.18)	-
Player class Realistic	0.40* (0.17)	-
Player class Pessimistic	-0.06 (0.12)	-
R ²	0.26	0.31
AIC/QIC	1810	601
Correlation structure	AR-1	AR1
Correlation parameter	0.36 (0.03)	0.41
Scale parameter	0.59 (0.03)	0.57
Number of clusters	102	34
Clusters size	15	15
Observations	1530	510

Note: Standard errors are in brackets.

*Indicates significance $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$.

†Player classes are characterized by both belief errors and intended behavior (harvest decisions) to others pledge (Table 3): Optimistic; Pessimistic; Realistic and Consensual; Free rider; Altruistic.

4. Discussion

The objective of this study was to experimentally investigate the effects that endogenously driven, abrupt changes (i.e. tipping points) of the economic environment may produce on the harvest and management decision of the EABFT (a CPR). We found that the existence of a latent and endogenous economic shift significantly influenced resource decision maker strategies regarding management cooperation and resource exploitation. Unlike our theoretical predictions (Hypothesis 1), when the threat of a regime shift was present, we observed relatively more cooperative behaviours and a more precautionary management of the renewable resources. We also observed more cooperation when the position of the tipping point is uncertain, rejecting our second hypothesis (Hypothesis 2). The threat of substantial losses associated with the shift in economic conditions significantly increased the likelihood of coordinating actions.

Our results about the influence of a tipping point on resource exploitation strengthen previous observations by Schill et al. (2015) and Lindahl et al. (2016). They demonstrated that a certain or a highly probable endogenous shift affecting the productivity of the resource creates the condition to avoid a disaster such as a stock exhaustion. Similarly, avoiding an economic disaster in a one-shot public good game with threshold is possible when it is in the interest of each individual (disaster is severe enough) to coordinate and contribute accordingly (Barrett & Dannenberg 2012; Barrett & Dannenberg 2013). But in contradiction with our theoretical expectation, uncertainty around the position of the tipping point influences exploitation strategies, enhancing instead of decreasing cooperation. Deviations from predictions in uncertain decision problems are well known. From empirical evidence, we know that in complex and uncertain decision problems (as used in our experiment), the assumptions underpinning the expected utility theory are questionable (e.g., Tversky and Kahneman 1974). Decision makers typically deviate from expected utility maximization and rely instead on heuristics (Moxnes, 1998 and Hey et al., 2009). Such theoretical biases bring insight to our experimental observations which deviate from theoretical predictions and from previous static design results. However, this result challenges previous findings obtained with one-shot public good games under uncertain threshold, in which the uncertainty level around the position of the threshold switches the game outcome from coordination to prisoner's dilemma (Barrett & Dannenberg 2013). Observations have shown that participants decreasing their contribution under uncertainty regime to an insufficient level would incur high economic loss and may not avoid the disaster (e.g. cost due to climate change effects, in Barrett & Dannenberg, 2013).

By introducing complex resource dynamics and incomplete information conditions into the experimental design, the focal point represented by the cooperative solution changes over time and is path-dependent. The incentive to deviate from a past agreement increases throughout time, as the probability of a game continuation decreases. Such conditions make cooperation and coordination more unlikely. This has been demonstrated experimentally by Herr et al. (1997) and Mason & Phillips (1997) when comparing static and dynamic designs.

Another interesting observation concerns the rare cases of groups (3 cases over 34) maintaining the biomass level close to the long term optimal level (40 units) in our experiment. The complexity and the high competitive feature of the experiment do not allow an agreement to emerge efficiently with only the threat of using trigger strategy. Another explanation of the weak cooperation level in our experiment could be related to the communication which has been reduced to implicit communication through pledges in this experiment. An important factor which has been excluded from our experiment is the introduction of face-to-face communication. Previous CPR research works show that face-to-face communication is important to determine whether groups will cooperate or not (e.g., Ostrom 2006). In complex

ecological dynamic experiments, Schill et al., (2015) and Lindahl et al. (2016) have shown that the effectiveness of communication (group agreements), which underlies cooperation, can be endogenous to the decision problem. The latent regime shift that people perceive as a threat in their experiments seems to be the trigger of communication between subjects.

Finally, we found a clear trend of non-cooperative (myopic) strategies over time regardless of the treatment. We found a strong correlation between non-cooperative strategies and the scarcity of natural resources. Subjects are prone to competitive and more intensive fishing behavior when the resource becomes scarcer. More surprisingly, the high cost of exceeding the threshold does not affect this pattern. This result confirms previous findings by Osés-Eraso et al. (2008). They had observed that users responded to scarcity with caution by observing directly harvest levels but were, nevertheless, not able to avoid resource extinction. If we observed directly the harvest instead of the ratio between harvest and the myopic harvest level, subjects would have decreased their catch levels. But the latter do not represent a good indicator of the cooperation level. When the situation becomes more competitive, with fewer natural resources to share, participants' behaviors seem to be driven by myopic strategies.

Our experiment is set in the context of the international management of a highly migratory fish, the Atlantic Bluefin tuna (EABFT) fishery and reproduces a stylized representation of the decision making process in the International Commission for the Conservation of Atlantic Tunas (ICCAT), to the notable exception of communication exchanges between participants. Our results confirm the possible change of management behaviours confronted to the threat of a shift in economic conditions. This situation is somehow close to the context of trade ban in 2009 jeopardizing the future of the EABFT fishery, which has resulted in a dramatic decrease of quotas (TACs) accepted by the fishing nations. When a critical threshold is introduced, decision makers coordinate their efforts in order to avoid exceeding the potential threshold, becoming more efficient, decreasing the rent dissipation and improving the sustainability of the resource. We know from previous CPRs experiments the importance of direct communication in the setting of cooperative agreements between participants (i.e Schill et al., 2015 and Lindahl et al., 2016). We leave to future works, the analysis of direct communications on cooperation in our CPR dilemma. It is worthwhile noting that our results stem from laboratory experiments with students as subjects. To increase confidence in our results, a next step would be to replicate this design into the "battle field", i.e. an international central institution such as the ICCAT commission with actual policy makers.

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7. Supplementary materials

7.1. Appendix A. Instructions.

Instructions T0

It is an experiment dealing with economic decision-making. We ask you to carefully read the instructions. When all the participants have read these instructions an experimenter will proceed to a re-reading aloud. We will then ask you to watch attentively a tutorial video to familiarize yourself with the web interface of the experiment.

From now on, we ask you not to speak anymore. If you have a question raise your hand and an experimenter will come to answer you privately. During the experiment, all your decisions will be treated anonymously. You will indicate your choices on the computer in front of which you are seated.

General instructions

This experiment has two parts. These instructions concern both parts 1 and 2 of the experiment. One of these two parts will be chosen by drawing lot for your remuneration. Your earning at this game will constitute your gain for the experience. It will be paid in cash at the end of the experiment.

In this experiment, each of you is a policy maker of a country involved in the East Atlantic bluefin tuna fishery. You and 2 other participants will form a group. You and your group members will have a common access to the Atlantic bluefin tuna resource. Each of you, at each round (which represents one year), will decide how many units (tons) of the resource you would like to harvest. These catches will bring you earnings in units of profit (euros).

Before making your decision, you will have to announce your catch to the other players, without the latter engaging you in your future private decision: you will be able to follow it or not. At the

same time, you will also estimate the cumulated catches of the other 2 members of your group. Finally, to make your private catch decisions, you will have access to catch proposals from other members of your group as well as information on the state of the resource from the International Commission for the Conservation of Atlantic Tunas (ICCAT).

Each part of the experiment lasts a certain number of rounds (years in the experiment), the amount of rounds is unknown to you. The experiment also ends if the resource is depleted due to excessive catches.

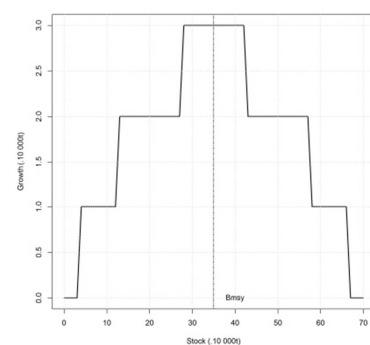


Figure 1

Remuneration

If you follow the instructions carefully and take sound decisions, you can earn money. One of the games will be chosen by drawing lot for your remuneration. Your earning at this game will constitute your gain for the experiment. Each profit you have accumulated by exploiting the resource during each game separately will be converted into euros at a rate of 1 monetary units of profit = 0.05€. You will begin each part of the experiment with 50 profit units, corresponding to 2.50 €. You will also be compensated for your exact expectations of the catch levels of the other participants, 0.20€ for each exact expectation.

Resource dynamic

The bluefin tuna resource increases in each round depending on the size of the resource at the beginning of the round, which in turn depends on the total harvest of the previous round (sum of your and the other participant's harvest in the previous round).

The exact relation between the size of the resource stock and its regeneration is illustrated in Figure 1. As the figure illustrates, if the total amount of catches exceeds the regeneration rate for the round, the resource stock will decline. Contrariwise, if the total amount of catches is inferior to the regeneration rate for the round, the resource stock will increase the next round. The Maximum Sustainable Yield (MSY) indicated on the figure (from 28 to 42 resource units) is the maximum amount of catch that allows the stock to remain constant from one round to the next. For example if the resource stock is 50 units of the resource at the beginning of a round. If you, harvest together with the 2 other members of your group 10 units in this round, the resource will regenerate itself by 2 units and, hence, the resource stock will be $(50 + 2 - 10)$ 42 units in the next round.

Harvest choice

Each round, you will receive information about the resource stock size available and harvest proposals from the 2 other members of your group. Depending on the part of the experiment the information about the resource stock size will be accurate or not. If this information is not accurate you will be aware of a range of equal possible value of the resource stock size each round for which you can deduce your possible profits.

Based on this information, you will choose how many units of resource you would like to harvest with a choice between 0 to 5 units. You, and the 2 other members of your group could harvest each round a total of 15 units. This amount of catch will bring you earning which depends on your harvest level, but also on the

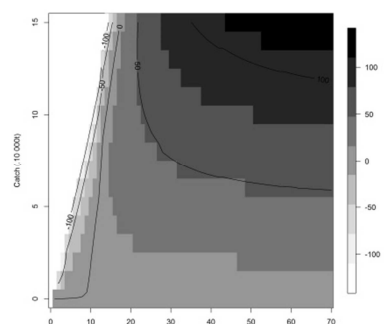


Figure 2

730 harvest level of the 2 other participants and on the resource stock size. The relation between
731 your profit, the total amount of catch from your group and the resource stock size is illustrated
732 in Figure 2. As illustrated in Figure 2, the most the resource is depleted the less you could earn
733 from harvest.

734 Your harvest decision is private but will be made public at the end of each round.

735

736 **Some rules**

- 737 • Talking is not permitted.
- 738 • You are not permitted to operate other software such as email or web pages during the
739 experiment.
- 740 • You may ask questions to the experimenter during the experiment if you have any
741 problems.

742 Before starting the experiment, you will be invited to follow a tutorial video presenting the web
743 interface of the experiment. Once this video has been watched, you can then complete the
744 identification form on the application page and fill in the comprehension test. Once the test has
745 been completed, you will have the opportunity to ask questions about the elements of the
746 experiment. Finally, at the end of the experiment, you will have to complete a short survey about
747 the experiment, and then you will have to wait until the experimenter calls you individually to
748 receive your payment.

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7.2. Appendix B. Pre-experimental survey and test.

About you

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Before beginning the session please give us some information about your profile.

Your name:

Your profession:

Your age:

Are you concerned with the subject of this study :

☐

Next

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752

Test

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Before beginning the session, We want to make sure that you understand the dynamic process which drive the resource level.

First of all, if at the beginning of the year the biomass is at a level of $25 \cdot 10^4$ t, could you indicate how many units (in 10^4 t) the stock will grow for the next year ? Use the growth function.

Resource growth in 10^4 t for the year:

Then, still with a stock of $25 \cdot 10^4$ t if the 3 nations decide to harvest $9 \cdot 10^4$ t, could you indicate how many profit (in 10^7 €) the harvest will generate this year? Use the profit function and round the value.

Total profit in 10^7 € for the year:

Under the same conditions, if the 3 nations decide to harvest $9 \cdot 10^4$ t ($3 \cdot 10^4$ t each), Could you indicate how many profits in 10^7 € you will win this year (individual profit)?

Use the table of individual profits.

Individual profit in 10^7 € for the year:

Next

7.3. Appendix C. Payoff and stock (biomass) variation table used in the experiment for a resource size of 50 units. On the top the “Payoff table” and on the bottom the

Individual profit											
My harvest	Sum of choices made by others										
	0	1	2	3	4	5	6	7	8	9	10
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	8.1	8.0	8.0	8.0	8.0	8.0	7.9	7.9	7.9	7.9	7.8
2	16.1	16.0	16.0	16.0	15.9	15.9	15.8	15.8	15.7	15.7	15.6
3	24.1	24.0	23.9	23.9	23.8	23.7	23.7	23.6	23.5	23.4	23.4
4	32.0	31.9	31.8	31.7	31.6	31.6	31.5	31.4	31.3	31.1	31.0
5	39.9	39.8	39.7	39.6	39.4	39.3	39.2	39.1	38.9	38.8	38.7

Biomass variation rate (%)											
My harvest	Sum of choices made by others										
	0	1	2	3	4	5	6	7	8	9	10
0	4	2	0	-2	-4	-6	-8	-10	-12	-14	-16
1	2	0	-2	-4	-6	-8	-10	-12	-14	-16	-18
2	0	-2	-4	-6	-8	-10	-12	-14	-16	-18	-20
3	-2	-4	-6	-8	-10	-12	-14	-16	-18	-20	-22
4	-4	-6	-8	-10	-12	-14	-16	-18	-20	-22	-24
5	-6	-8	-10	-12	-14	-16	-18	-20	-22	-24	-26

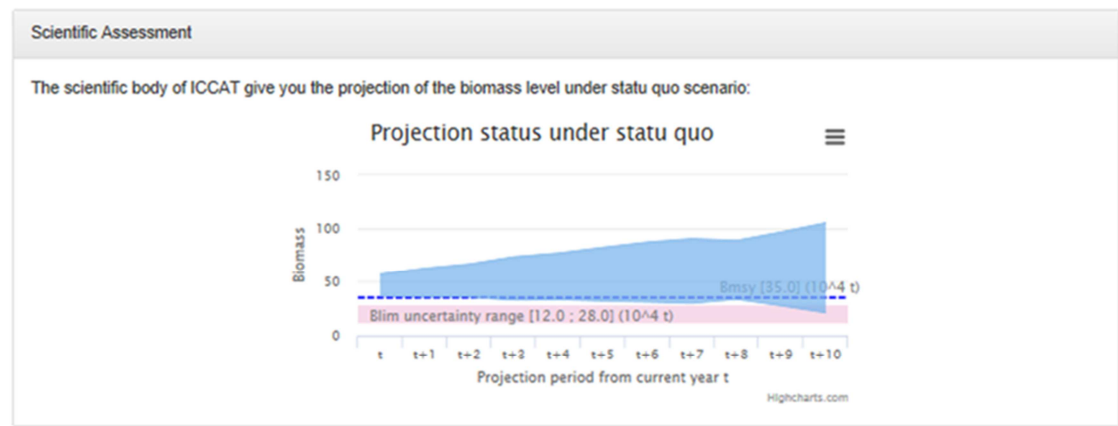
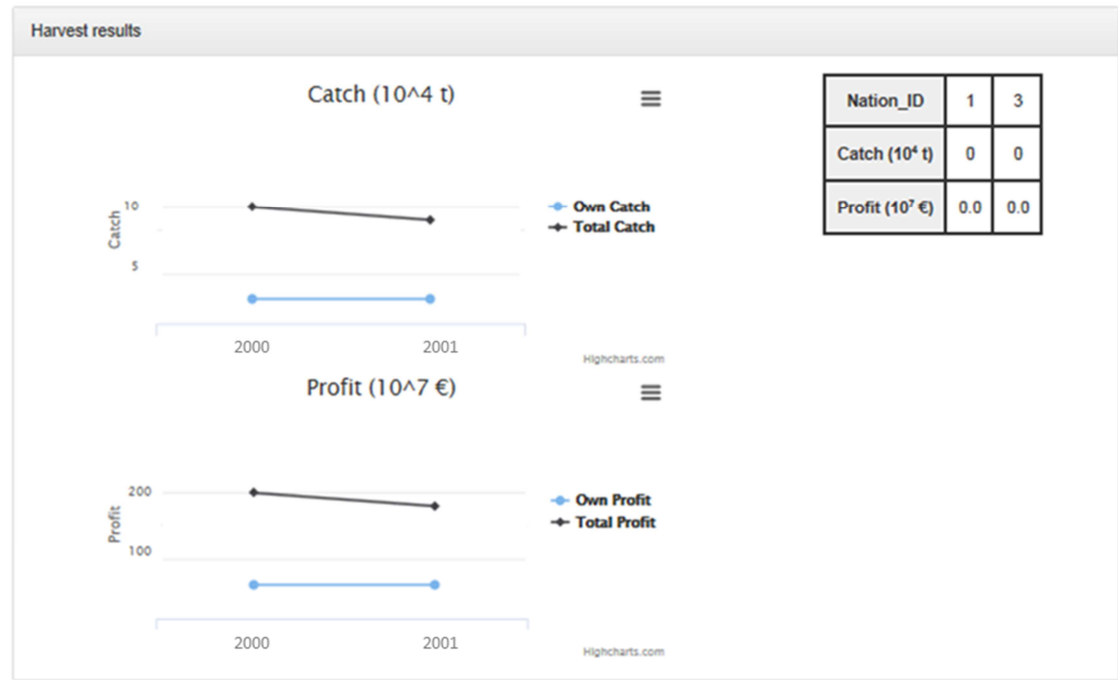
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7.4. Appendix D. Harvest results and stock (biomass) projection example.

Results from harvest

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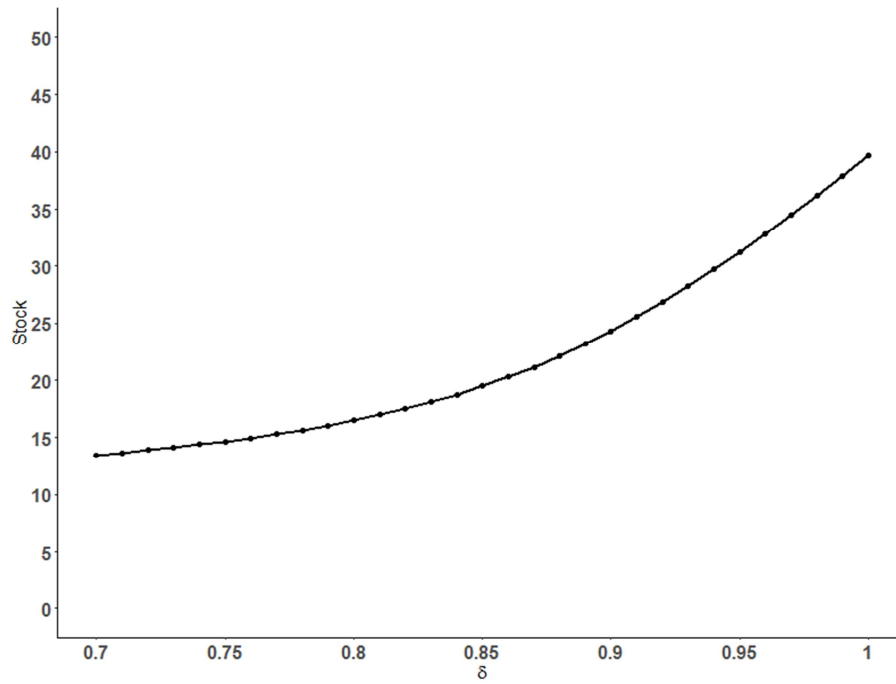
You have selected an harvest of 0 (10⁴ t). Your profit for the last year is 0.0 (10⁷ €).
Your total profit since the beginning of the fishery is 0.0 (10⁷ €).
This is equivalent to a real payment of 0.0€ Plus a bonus payment for your expectations of the level of exploitation of other nations of euros0.20 €.
ICCAT commission gives you also the statistic from the total catch and profit realized last years.



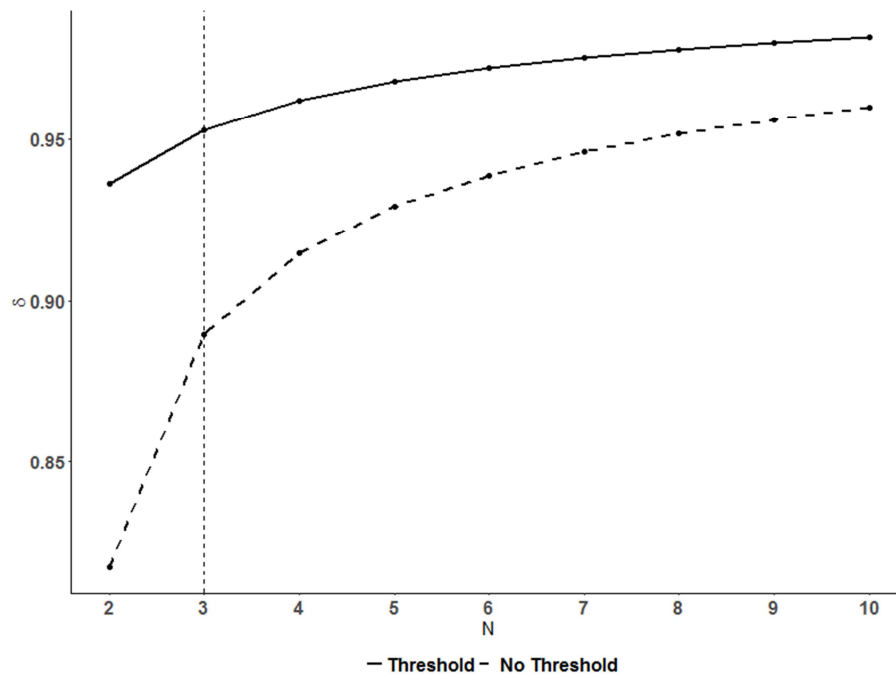
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7.5. Appendix E. Relationship between the optimal stock level (B_{opt}) and the discount factor (δ).



7.6. Appendix F. Relationship between the maximum number of players (N) in a cooperative solution and the minimum discount factor (δ).



7.7. Appendix G. Myopic symmetric paths.

Considering that all participant have the same payoff function, we restrict the analysis to symmetric outcomes in which each participant uses the same harvests strategy y^e). In this context a participant i seeks to maximize his profit flow by selecting an harvest strategy. Letting δ represent the discount factor, common to all participants, the present discounted value of profit in period t , $V_{i,t}$ of each participant, satisfies the Bellman's recursion equation:

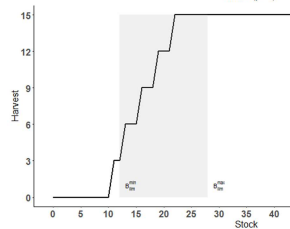
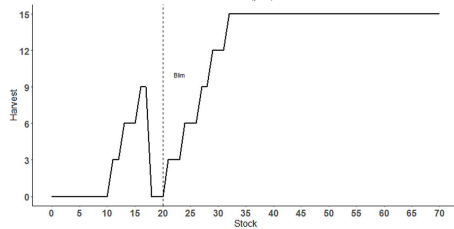
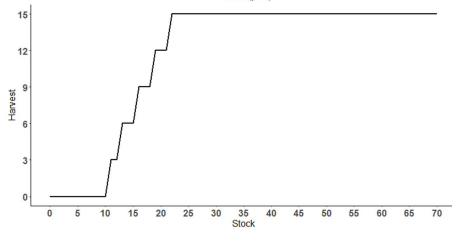
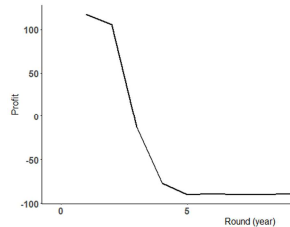
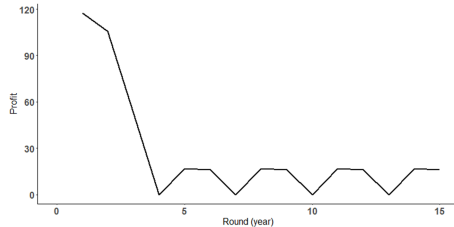
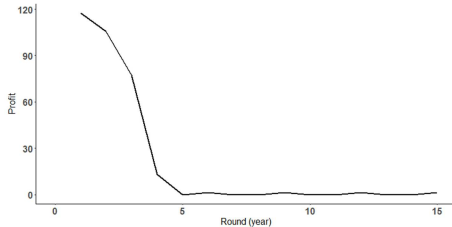
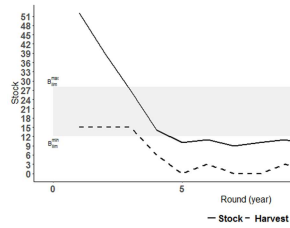
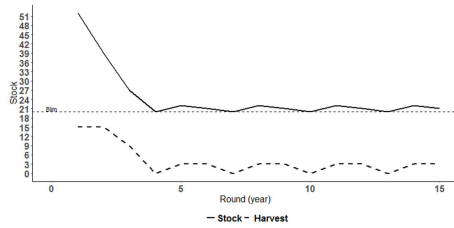
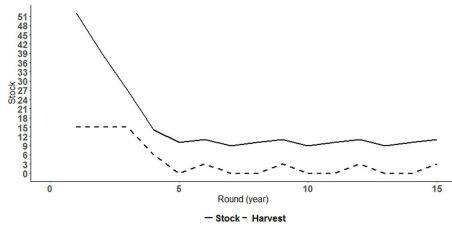
$$V_{i,t} = \text{Max}_{y_{i,t}} (\pi_{i,t} + \delta \cdot V_{i,t+1}) \quad (\text{H1})$$

$$\text{s.t } B_{t+1} = B_t \cdot \left[1 + r \cdot \left(1 - \frac{B_t}{K} \right) \right] - (N - 1) \cdot y_t - y_{i,t}$$

$$y_t = y^e(B)$$

Myopic behaviors result from neglecting the fact that current extraction decreases the future value of the resource is defined by backward recursion of the Bellman equation H1 considering the discount factor δ which tends to 0. Therefore, we define the collective (N participants) myopic path for each experimental treatment: without tipping point, when a tipping point is introduced and when the position of the tipping point is uncertain (on the left, middle and on the right respectively). We consider risk-neutral players when the position of the tipping point is uncertain. The risk neutral players based their harvest strategy upon the following profit function:

$$\pi_{i,t} = \begin{cases} p \cdot y_{i,t} - C(B_t) \cdot \frac{y_{i,t}}{Y_t}, & \text{for } B_t > B_{\text{lim}}^{\text{max}} \\ p \cdot y_{i,t} - C(B_t) \cdot \frac{y_{i,t}}{Y_t} - \alpha \cdot \left[1 - \left(\frac{B_t - B_{\text{lim}}^{\text{min}}}{B_{\text{lim}}^{\text{max}} - B_{\text{lim}}^{\text{min}}} \right) \right], & \text{for } B_t \in [B_{\text{lim}}^{\text{min}}, B_{\text{lim}}^{\text{max}}] \\ p \cdot y_{i,t} - C(B_t) \cdot \frac{y_{i,t}}{Y_t} - \alpha, & \text{for } B_t < B_{\text{lim}}^{\text{min}} \end{cases} \quad (\text{H2})$$



786 **7.8. Appendix H. Phase effects.**

	Phase 1	Phase 2	p (Mann-Whitney-Wilcoxon test, χ^2 or Fisher's exact test) [†]
Average group harvest as a fraction of myopic strategy	0.68 (0.67)	0.67 (0.74)	0.92
Average group stock	25.94 (15.41)	25.75 (15.71)	0.87
Proportion of group crossing the threshold	0.64	0.64	1.00
Average group profit	4.60 (28.17)	5.00 (28.22)	0.92
Average group harvest	1.49 (1.64)	1.48 (1.70)	0.97
Average group pledge	1.19 (1.52)	1.12 (1.47)	0.49
Average group belief error	-0.67 (2.89)	-0.70 (2.92)	0.81
Average group intended behavior	0.30 (1.68)	0.36 (1.69)	0.65

Note: Standard errors in brackets.

*Indicates significance $p<0.05$, ** $p<0.01$ and *** $p<0.001$.

[†] Mann-Whitney-Wilcoxon test is used to compare means across phases and χ^2 or Fisher's exact test (depending on the case frequencies) used to compare proportions across treatments and phases (see Appendix 6 for information on statistical analysis).

787

788 **7.9. Appendix I. Random effect generalized linear mixed model (GLMM) regression.**

Binomial regression models	Random group effect GLMM regression Best model	Random group effect GLMM regression Best model
	Harvest as fraction of myopic strategy	Mean group harvest as fraction of myopic strategy
Intercept	1.40 *** (0.28)	2.45 *** (0.31)
Treatment 1	-1.32*** (0.30)	-1.19** (0.48)
Treatment 2	-1.39*** (0.32)	-1.31** (0.51)
Biomass	-0.05*** (0.005)	-0.05*** 0.008)
Player class Consensual [†]	0.47* (0.22)	-
Player class Free-rider	1.10*** (0.18)	-
Player class Realistic	0.52* (0.27)	-
Player class Pessimistic	0.38* (0.18)	-
R ²	0.27	0.26
AIC/QIC	1676	578
Number of clusters	34	34
Clusters size	45	15
Observations	1530	510

Note: Standard errors are in brackets.

*Indicates significance $p<0.05$, ** $p<0.01$ and *** $p<0.001$.

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