# Fixed Instruments to Cope with Stock Externalities

## An Experimental Evaluation

Gastón Giordana and Marc Willinger

NOTA DI LAVORO 72.2007

**JULY 2007**

ETA – Economic Theory and Applications

Gastón Giordana and Marc Willinger, *LAMETA, Université Montpellier I*

Corso Magenta, 63, 20123 Milano (I), web site: www.feem.it, e-mail: working.papers@feem.it

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### Summary

We evaluate the effectiveness of non optimal and temporally inconsistent incentive policies for regulating the exploitation of a renewable common-pool resource. The corresponding game is an N-person discrete-time deterministic dynamic game of $T$ periods fixed duration. Three policy instruments with parameters that remain constant for the whole horizon are evaluated: a pigouvian tax *(flat tax)*, an ambient tax *(ambient flat tax)* and an instrument combining the two previous ones *(mixed flat instrument)*. We test in the lab the predictions of the model solved for 3 distinct behavioural assumptions: (a) sub-game perfection, (b) myopic behaviour, and (c) joint payoff maximization. We find that subjects behave myopically in the unregulated situation, which agrees with previous results in the literature. Conditional on predictions, the *mixed flat instrument* and the *flat tax* are the most effective policies in approaching the optimum extraction path. However, in absolute terms the *ambient flat tax* and the *mixed flat instrument* curb most significantly the mean extraction path towards the optimum path. Paradoxically, these instruments are the less efficient ones.

**Keywords:** Policy Instruments, Renewable Common-pool Resources, Dynamic Externalities, Experimental Economics

**JEL Classification:** D9, D62, H23, H26, H30, Q20, Q28

*We would like to thank Mabel Tidball, Marielle Montginoul and Bertrand Aunay for their stimulating discussions and valuable comments as well as the participants of the SysCoLag seminars. We acknowledge the Languedoc-Roussillon Region and IFREMER for financial support.*

*Address for correspondence*:

Gastón Giordana
LAMETA, Université Montpellier I
Av. de la Mer - Site de Richter - C.S. 79606
34960 Montpellier Cedex 2
France
E-mail: giordana@lameta.univ-montp1.fr

## 1. Introduction

Managing the exploitation of renewable natural resources, designing policies aimed at reducing water or air pollution, or fighting against global warming, requires taking into account stock externalities. Unlike static externalities whose detrimental effects disappear after some time, stock externalities generate persistent effects due to the accumulation process. Examples include greenhouse gases emissions, groundwater withdrawals, fisheries exploitation, etc.... In contrast to static externalities, which may be remedied by policies correcting inefficient decisions, for stock externalities no instant policy is capable to remediate immediately the damage created in previous periods. Once the resource stock has been deteriorated current policies can only curb the dynamic externalities beyond the current period. Empirical and experimental findings showed that in a dynamic environment, resource exploitation can lead to dramatic inefficiencies, enhancing the need for effective policies to cope with them (Clark, 1974; Herr et al, 1997; Giordana, 2007). In this paper, we analyze policy instruments targeted to achieve a second-best withdrawal path in the case of a common-pool renewable resource.

The literature on externalities puts traditionally forward Pigouvian taxes as a particularly adapted policy for correcting externalities (Baumol and Oates, 1988), although unit taxes are inefficient when the regulator cannot observe individual actions. Observability of individual actions rests on the availability of monitoring technologies and/or negligible observational costs (Millock et al, 2002). If such technology is available, unit taxes can be enforced by the regulator through incentive mechanisms such as random auditing combined to penalties in case of detected shirking (Becker, 1968; Polinsky and Shavell, 1979; Kritikos, 2004). If monitoring technologies are not available, or observational costs are prohibitive, in most instances the regulator can nevertheless periodically observe the state of the resource. Instruments developed initially to cope with nonpoint-source pollution can be implemented efficiently in these cases (e.g. the ambient tax).

In a dynamic framework with a finite horizon, policy parameters can be adjusted from one period to the next to adapt incentives to the observed state of the resource and to the remaining time. Efficient internalization of a dynamic externality can therefore be achieved by adjusting the tax rate, the penalty, and the targets after each period (Xepapadeas, 1991; Xepapadeas, 1992; Xepapadeas, 1994). From a practical point of view, the implementation of such a dynamic policy instrument is generally not feasible; the regulator's policy choice set is therefore constrained. We consider two types of constraints on the regulator's choice: technical constraints and ethical constraints. Technical constraints on policy instruments are due to behavioural heterogeneity, lack of relevant information or transaction costs for adjusting targets and instruments. We assume that these constraints restrict the regulator's choice set to 'fixed' - non optimal - instruments (Ko et al, 1992). In contrast to optimal instruments, fixed instruments are characterized by constant policy parameters all along the temporal horizon. Nevertheless, even with fixed instruments the first best withdrawal trajectory can be achieved. Ethical constraints however put more stringent restrictions on the policy choice set. Take the example of the ambient tax and assume that all agents do not behave rationally. Whenever total withdrawals are off the target trajectory, all agents are liable to pay a fine even if they did not free ride. Such instruments might therefore be politically or ethically unacceptable with the implication that the first best withdrawal path can no longer be achieved. In this paper, we assume that the regulator is might be constrained to implement instruments that achieve only a second best extraction path. We consider therefore two types of fixed instruments in this paper: first best fixed instruments when only technical constraints restrict the regulator's choice set and second best fixed instruments when also ethical constraints apply.

We provide an experimental evaluation of alternative policies to cope with the dynamic externalities generated by the exploitation of a renewable common-pool resource. The reason why we chose to rely on an experimental approach is that most of these instruments have not yet been implemented in the field. Our paper relates to the work of Herr et al (1997) which compares the efficiency of the exploitation of a non-renewable common-pool resource that generates either only static externalities or both dynamic and static externalities. Their results witness for the increased inefficiency of the resource exploitation when a dynamic framework is considered. We implement a similar experimental protocol and introduce three extensions to their work: (i) the common-pool resource is renewable, (ii) we consider only dynamic externalities, and (iii) we evaluate policy instruments to correct the inefficiencies. The two first extensions rely on empirical considerations. Actually, many common-pool resources are renewable (e.g. fisheries, forests, aquifers) and depending on some intrinsic characteristics their exploitation may or not generate intra-period external costs. We compare three alternative non optimal instruments: (*i*) a fixed tax rate on declared extractions combined with a compliance monitoring mechanism *(flat tax)*; (*ii*) the ambient tax based on Segerson (1988) with fixed tax rates and fixed targets (*ambient tax)*; and (*iii*) a mixed instrument combining the two previous instruments based on Kritikos (2004), (*mixed flat instrument)*. We consider three kinds of benchmark behavior -myopic, rational and optimum- and discuss the corresponding symmetric solutions of the dynamic game, respectively, the per-period Nash equilibrium outcome, the sub-game perfect equilibrium outcome, and the joint profit maximizing outcome. Under myopic behaviour the optimization horizon is restricted to one period; withdrawers do not consider the impact of their actual extractions on their own future profits. The myopic player assumes that all other players behave myopically, and therefore a Nash equilibrium is calculated for each period. Under rational behaviour, farsighted selfish withdrawers internalize the impact of their current extraction decision but just on their own future returns. Sub-game perfection is the solution concept applied to this game. The optimum outcome consists in the decision that maximizes the sum of all withdrawers' profit for the whole temporal horizon. On the optimum extraction path, no externalities are generated. However, in this kind of social dilemmas this strategy is dominated.

We summarize our main findings as follows. Subjects behave myopically in the unregulated situation, which agrees with previous results in the literature. Conditional on predictions, the *mixed flat instrument* and the *flat tax* are the most effective policies in approaching the optimum extraction path. However, in absolute terms the *ambient flat tax* and the *mixed flat instrument* curb most significantly the mean extraction path towards the optimum path. Paradoxically, these instruments are the less efficient ones. In our dynamic game stock saving implies forgone earnings that must be "cashed" in future periods by extracting the optimal quantities, otherwise losses become significant. This suggests that care must be paid in the practical implementation of time inconsistent instruments, since early deviations from predictions alter the incentives set by each policy, either encouraging non optimal behaviour or just confusing subjects with distorted signals.

Section 2 introduces the dynamic exploitation game of a renewable common pool resource. The predicted path for each behavioural assumption is derived and the corresponding policy instruments are discussed. Section 3 introduces the experimental design and the predicted paths obtained with our parametric choice. Section 4 exposes the results: firstly, the fitting of the data to the theoretical predictions, and secondly the efficiency and effectiveness of each policy instrument. Section 5 concludes.

## 2. A Discrete Dynamic Game of Common Pool Resources' Exploitation

Our experiment is based on a discrete finite time dynamic game of CPR exploitation. We first introduce the model before discussing possible solutions depending on alternative behavioural assumptions.

Assume that $N$ identical appropriators, indexed by $i$, extract units from a common resource in each period, $t = 1,...,T$. The resource is characterized at each period $t$, by a stock of available units. In period $t$ appropriator $i$ withdraws the quantity $y_i^t$. The evolution of the resource stock is described by equation (1):

$$S^{t+1} = S^t - Y^t + r \tag{1}$$

where, $S^t$ is the stock of available units of the resource in the beginning of period $t, r$ is the natural per period recharge[1], and $Y^t = \sum_{\forall i} y_i^t$ is the total extraction in period $t$.

According to Equation (1), the groundwater stock grows naturally[2] with the recharge and decrease with extractions.

Extracted units generate a gross return to appropriator $i$ in period $t$, given by:

$$u_i(y_i^t) = a \cdot y_i^t - b \cdot (y_i^t)^2 \tag{2}$$

where $a,b > 0$.

The average extraction cost from the CPR depends linearly on the available stock and on total extractions of the period:

$$AC(S^t, Y^t) = p + z \cdot Y^t - f \cdot S^t \tag{3}$$

where $p,z,f \geq 0$. $z$ measures the within period externality, and $f$ measures the across period externality[3]. Since there is free access to the resource, the period $t$ profit of each appropriator (we drop the index $i$) is given by:

$$U(y^t) = u(y^t) - AC^t \cdot y^t \tag{4}$$

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[1] Note that we assume a constant recharge in our model.

[2] If there were no extractions the resource stock would grow indefinitely. A more complete specification of the resource dynamics should define a natural out-flow or disease rate.

[3] In many empirical situations only across-period externalities are present. For example, in the case of groundwater exploitation there is no reason to think that pumping on the same basin by two individuals remotely located, will mutually affect each other's net return within a period (Brozovic, 2006).

We assume that appropriator *i*'s objective function in each period *t* is to maximize the discounted sum of his profits, $\sum_{s=t}^{T} \rho_i^{s-t} \cdot U^s$ . Let $W_i^t$ be appropriator *i*'s accumulated wealth in period *t*:

$$W_i^t = W^0 + \sum_{s=1}^{t} U_i^s \qquad \forall i, \tag{5}$$

where $W_i^0$ is appropriator i's initial wealth. Appropriators may have different discount rates. Since we have no financial markets in the model, the interpretation is that appropriators' preferences for the present are heterogeneous. For sake of simplicity we allow $\rho_i$ to take just two values in the set $\mathrm{P} = \{0,1\}$, which is assumed to be common knowledge. We call "myopic", appropriators who totally discount future benefits, and "rational", appropriators who do not discount the future. Behaviourally speaking rational appropriators are farsighted, i.e. they internalize the impact of their current extractions on their own future profits. In contrast, myopic appropriators just care about their current profit neglecting any future impact of current extractions.

### *2.1 Laissez faire*

In a situation with no public intervention we derive different benchmark solutions for the extraction game. We consider three kinds of behaviour, which correspond to three symmetric solutions of the game[4]: the sub-game perfect equilibrium outcome (farsighted appropriators), the myopic outcome (myopic appropriators), and the joint profit maximization outcome (cooperators). Let us call these benchmark solutions the Rational, Myopic and Optimum outcome, respectively.

Rational appropriators internalize the impact of their current extractions on their own future profits. They define an optimal extraction plan, which is a best response to the other players' optimal extraction plans. This extraction plan is called feedback strategy if it is a function of the available stock in each period *t*. Such a solution needs a particular information structure; appropriators must perfectly observe the available stock of the resource at the beginning of each period (Basar and Olsder, 1999), which allows them to adapt their extraction plan to every period's conditions[5]. Conversely, if appropriators do not observe in every period the available stock, but just the initial stock at the beginning of the game, they will not be able to periodically adapt their extraction plan. In that case, rational appropriators implement an open-loop strategy (Basar and Olsder, 1999)[6].

Under the assumption of myopic behaviour, the optimization horizon is restricted to one period. Each period the myopic appropriator calculates the profit maximizing extraction given the best responses of his rivals. In each period of the game, except the last one, myopic behaviour leads to higher extractions compared to rational behaviour, given the resource stock available in period *t*. Rational appropriators are able to take into account in their actual

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[4] Every appropriator in the population has the same time preferences and no preference reversals are allowed.

[5] There is no commitment on extraction decisions (see Levhari, D. and L. J. Mirman (1980), Levhari, D., R. Michener, et al. (1981), Reinganum, J. and N. Stokey (1985) as examples of such strategies applied to modeling the fisheries exploitation).

[6] Hence, there is full commitment to a fixed extraction path.

decision the future periods' natural recharge of the available stock. The larger the natural recharge the greater is the gap between rational and myopic extractions trajectories.

The optimum outcome is derived by maximizing the aggregate profit of all appropriators' over the temporal horizon. The corresponding trajectory would be obtained by a benevolent regulator or by perfect cooperation of the appropriators, which both imply joint profit maximization. The optimum extraction path has a positive slope which is vanishing in the case where the natural recharge is null.

The extraction game involves a social dilemma, since the cooperative outcome is a dominated strategy. We therefore investigate various policy instruments that could be implemented by a regulator whose objective is to match the private incentives with the public objective.

### *2.2 Regulation*

We consider a regulator who has the option to set financial incentives in order to implement the cooperative outcome as the equilibrium strategy of the game. We assume that the regulator can choose among three alternative first best instruments: (*i*) a tax on declared extractions with a compliance monitoring mechanism; (*ii*) an ambient tax; and (*iii*) a mixed instrument combining the two previous instruments.

The optimal tax scheme requires two properties: zero fraud and internalization of the appropriation externalities (static and dynamic). The optimal individual tax rate $\tau_i^{t*}\left(S^t, Y^t, r, y_i^t, \rho_i\right)$ depends on the available stock, the total extraction, the recharge, the individual extraction and the discount rate. The resource stock and the natural recharge increase the optimal tax rate as enhance the dynamic externality. On the contrary, total extractions reduce the optimal tax rate because they shrink the dynamic externality by degrading future periods' resource stocks. Individual extractions have two conflicting effects on the tax rate. On one hand, the tax rate increases with individual extractions to internalize the associated static externality; on the other hand, the tax rate diminishes as individual extractions reduce the dynamic externality in the same way than the total extractions do. Concerning the discount rate, myopic appropriators face a higher tax rate than farsighted appropriators, for any resource stock and period (excepting the ending one).

In order to monitor compliance the regulator can audit a fixed number of appropriators in each period. We assume perfect audit: spot controls allow the regulator to observe the exact individual level of current extraction. Detected cheaters must pay a fixed penalty in addition to their tax debt. As appropriators do not know who has been audited in the period, all appropriators face the same audit probability. A risk neutral agent will avoid cheating if the penalty is equal to:

$$\Omega_i^t = \frac{U\left(S^t, y_i^t\right) - p \cdot \tau_i^t \cdot \left(y_i^t - \hat{y}_i^t\right) - \hat{y}_i^t \cdot \tau_i^t}{p}, \tag{6}$$

where, $p$ is the audit probability, $\hat{y}_i^t$ is the *i*th appropriator declared extraction. The lower the audit probability the higher the penalty required to encourage compliance. However, if limited liability constraints prevent high penalties to be enforced, first best solution may not be achievable.

In some cases appropriators can successfully hide extractions, avoiding penalties after a control. In such cases tax schemes are inefficient, and an instrument based on total extraction, if observable, might be indicated. Following Segerson (1988) a first best extraction path can be attained by implementing in each period an unbalanced collective penalty of the form:

$$\Gamma_i^t = \kappa_i^t \times \max\left[S^t + \sum_{\forall i} y_i^t - S^{t*}, 0\right] \qquad t = 1,\ldots,T. \tag{7}$$

Where $S^{t*}$ is the first best resource stock at the end of period *t*. With this instrument every appropriator pays for the extractions in excess of the target. An ambient tax rate $\kappa_i^t = \tau_i^{t*}\left(S^t, Y^t, r, \rho_i\right)$ introduces optimal incentives to first best extractions, implying that none of the appropriators is penalized at equilibrium. However, the ambient tax has many drawbacks (Kritikos, 2004). In order to avoid tax payments some appropriators may compensate excessive extractions of free riders resulting in multiplicity of equilibria. If coordination fails, innocent appropriators will be wrongly punished. Additionally, if penalties are high enough, limited liability constraints will prevent the ambient tax to be enforced on some appropriators and the first best solution will not be achieved.

The mixed instrument results from the combination of the previously described policies (Kritikos 2004). Under this policy, appropriators pay taxes on declared extractions and a collective penalty is levied if total declared extractions differ from the total extraction observed by the regulator. Furthermore, the regulator performs random *in situ* controls to track for cheating appropriators who must pay their tax debt and the collective penalty while the compliant appropriators are freed of paying the collective penalty.

The mixed instrument achieves the first best extraction path as a unique equilibrium, avoiding the limited liability constraints, whenever the collective penalty takes the following form (Kritikos 2004):

$$\Gamma_i^t = \tau_i^{t*} \times min\left[W_i^t, \sum_{\forall i} y_i^t - \sum_{\forall i} \hat{y}_i^t\right] \tag{8}$$

### 2.2.1 Policy choice

The practical implementation of any of the previously described instruments is costly; designing individual tax rates and adjusting them each period, identification of the appropriators' type, compliance monitoring and observation of relevant variables are costly activities. In practice the regulator has a limited budget to achieve the first best solution. Additionally, the regulator might be restricted in the policy choice by legal and political considerations. Furthermore, instruments might be adapted to ensure in each period a minimum profit to appropriators.

Let us suppose that the regulator cannot afford the identification of the appropriators' types nor the adjustment of the instruments' parameters from one period to another. The instruments are therefore implemented with uniform and fixed parameters, i.e. the tax rate would be the same for every appropriator's type and won't be adjusted over time. It can be shown that under certain conditions the previously described instruments, with uniform and fixed parameters, can successfully implement the first best extraction path (Giordana 2007).

### *2.2.2 Transformed policy instruments*

#### *(i) Flat tax*

We call *flat tax* a policy instrument resulting from the combination of a tax scheme (described in section 2.2) with a uniform and a fixed tax rate, and a subsidy equal to the tax payments if extractions are less than the first best extractions. Under the *flat tax* appropriators will pay a uniform tax on declared extractions:

$$\tau_i^t = \begin{cases} \bar{\tau} & \text{if} \quad y_i^t > y^{t*} \\ \\ 0 & \text{if} \quad y_i^t \leq y^{t*} \end{cases} \qquad \forall i, t \tag{9}$$

where, $y^{t*}$ is the period $t$ first best extraction resulting from an open-loop strategy.

If $\bar{\tau}$ is sufficiently high and there is total compliance, the *flat tax* can achieve the first best solution and no tax is levied in that case. Compliance is monitored in the same way described for the tax scheme (section 2.2).

#### *(ii) Ambient flat tax*

We call *ambient flat tax* the ambient tax defined by equation (7) but with a uniform and a fixed tax rate $\bar{\kappa}$:

$$\bar{\Gamma}_i^t = \bar{\kappa} \times \max\left[ S^t + \sum_{\forall i} y_i^t - S^{t*}, 0 \right] \quad t = 1, \ldots, T. \tag{10}$$

Similarly to the flat tax, the *ambient flat tax* can achieve the first best solution if $\bar{\kappa}$ is sufficiently high.

#### *(iii) Mixed flat instrument*

This instrument is similar to the mixed instrument described in section 2.2, but the tax rate is replaced by equation (9). Then, the *mixed flat instrument* is a first best policy if $\bar{\tau}$ is sufficiently high.

Under any of these transformed policy instruments the first best solution is attainable if the tax rates are correctly calibrated. Additionally, no tax is levied at equilibrium. Thus, myopic and farsighted appropriators will remain on the optimal extraction path (the optimum outcome). However, if the regulator is constrained to fix a tax rate smaller than the optimal one (as a consequence of political considerations), the optimum extraction path will be a dominated strategy. Then, under any of the flat instruments, each appropriator type (myopic and farsighted) will have different optimal feedbacks.

## 3. Experimental Design

The experimental protocol was designed to capture the fundamental aspects of the game described by equations (1)-(5). In each period, subjects decide the amount of “units” to extract from an account. Given the parameterization (see *Table 1*), in each period a subject earns experimental points depending on his/her unit order and on the available units in the account at the beginning of that period. We run 4 treatments: “Laissez-faire” (LF hereafter), which corresponds to the benchmark treatment without any policy instrument, the Flat Tax treatment (FT hereafter), the Ambient Flat Tax treatment (AFT hereafter) and the Mixed Flat Instrument treatment (MFI thereafter). The dynamic extraction game is played over 10 periods.

**Treatments**

| | Laissez faire (LF) | Flat tax (FT) | Mixed flat instrument (MFI) | Ambient flat tax (AFT) |
|---|---|---|---|---|
| Group size ($N$) | 5 | | | |
| Benefit function | $a = 5.3$<br>$b = 0.09$ | | | |
| Cost function | $p = 7.55$<br>$f = 0.01$<br>$z = 0$ | | | |
| Account evolution | $S^1 = 500$<br>$r = 30$ | | | |
| Available range of unit orders | $[0,50]$ | | | |

| **Policy instrument** | Laissez faire (LF) | Flat tax (FT) | Mixed flat instrument (MFI) | Ambient flat tax (AFT) |
|---|---|---|---|---|
| Tax rate & audit probability | x | $\bar{\tau} = 1$<br>$p = 0.2$ | $\bar{\tau} = 1$<br>$p = 0.2$ | $\bar{\kappa} = 0.2$<br>$p = 0$ |
| Individual penalty | x | $\Omega_i^t = \frac{U(S^t, y_m^t(S^t)) - p \cdot \bar{\tau} \cdot y_m^t(S^t)}{p}$ | $\bar{\tau} \times (y_i^t - \hat{y}_i^t)$ | x |
| Collective penalty | x | x | $\overline{\Gamma}_i^t = \bar{\tau} \times max[0, Y^t - \hat{Y}^t]$ | $\overline{\Gamma}_i^t = \bar{\kappa} \times \max[S^t + Y^t - S^{t*}, 0]$ |

**Table 1: Experimental parametric restrictions on the extraction model**

In order to reduce the complexity of the decision environment some simplifications have been introduced. Explicitly, no distinction was made between orders revenues and costs. Subjects knew only the net outcome of their withdrawal decision. Additionally, the individual penalty in the FT and MFI treatments was deeply simplified (Table 1). We have replaced in the penalty function (equation 6), the *i*th appropriator extractions ($y_i^t$) by the period *t* optimal feedback of myopic appropriators $\left(y_m^t\left(S^t\right)\right)$[7], and the *i*th appropriator declared extractions ( $\hat{y}_i^t$ ) by zero. In this way the individual penalty in each period reduces to a function of the available stock, becoming a lump-sum penalty. These simplifications were introduced to ease the participants' task, tough it implies a negative expected profit of non compliance.

### *3.1 Predictions*

Figures 1, 2 and 3 plot the extraction path of the myopic, rational and optimum strategies[8]. In the LF treatment, the extraction paths are clearly different for each strategy. While the myopic extraction path is decreasing (large amounts extracted in early periods due to impatient behaviour) the rational extraction path is quite stable. The strength of the "social dilemma" is at its maximum in the first periods as the optimum extraction path has a positive slope. Taking the optimum strategy as an efficiency benchmark[9], the myopic and rational strategies achieve, respectively, 74% and 51.8% of efficiency with respect to the benchmark.

The predictions for the FT and MFI are similar (Figure 2). The optimum prediction is the same as in the LF treatment (Figure 1). As can be seen, the myopic and rational strategies extraction paths approach the optimum, although not completely, compared to laissez faire. But there are large gaps in the first four periods and the last two periods. The rational and myopic strategies achieve, respectively 89.4% and 76% of gross efficiency. However, the efficiency net of taxes is smaller, 61.4% and 42.3% respectively. Actually, appropriators withdraw more than the optimum strategy, and pay the corresponding tax, because the tax rate is too low and compliance is ensured by the individual and collective penalties.

The strength of the "social dilemma" is smallest in the AFT treatment, as the extraction paths are closest to the optimum path. As a consequence, the predicted gross efficiency of this treatment outperforms the FT and MFI treatments. The rational and myopic strategies achieve, respectively 92% and 81.6%. Conversely, the net efficiency under the AFT is lowest. The rational strategy achieves 54.4% of net efficiency. The predicted accumulated wealth net of taxes under the myopic strategy is negative (net efficiency of -20.4%). Again the low tax rate fails to encourage myopic appropriators to refrain their withdrawals. Rational appropriators triplicate the myopic performance because they consider the impact of actual withdrawals on the size of the future collective penalty. Since the target path and the stock recharge are fixed for the whole temporal horizon, excessive orders in early periods may cause irreversible deviations from the target path in the future. Then, even if total orders are equal to zero in a future period, the period target may not be attained and the collective penalty levied.

### *3.2 Experimental Implementation*

All experimental sessions were conducted at the University of Montpellier 1 using the z-Tree computer programme (Fischbacher, 2007). Subjects were recruited from the pool of

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[7] We assume that the entire population behaves myopically.

[8] Predictions are calculated for each treatment assuming that all appropriators in the population follow the same strategy, i.e. rational, myopic or optimum strategies.

[9] We define efficiency as the wealth that has been accumulated until the end of period *T* under a particular strategy with respect to the optimum strategy.

undergraduate students of LEEM[10]. None of the subjects had ever participated in a similar experiment. Most recruitment was done by e-mail. Subjects were invited to participate in an experimental game lasting approximately one and a half hour, and were told that they will receive a cash payment based on their decisions and the decisions of the group (in addition to a show-up fee).

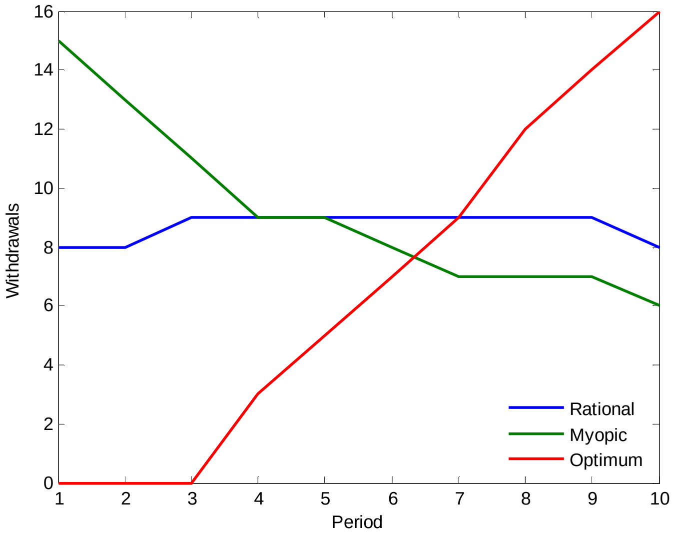

**Figure 1: Predictions of the laissez-faire treatment.**

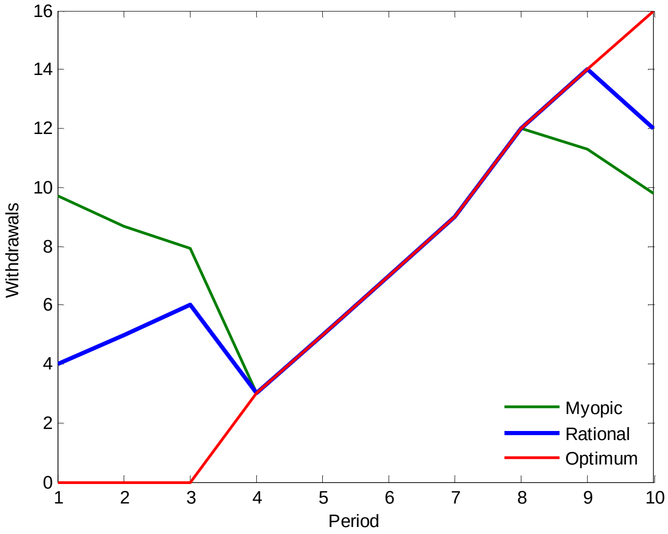

**Figure 2: Predictions of the FT and MFI treatments.**

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[10] Laboratory of Experimental Economics of Montpellier.

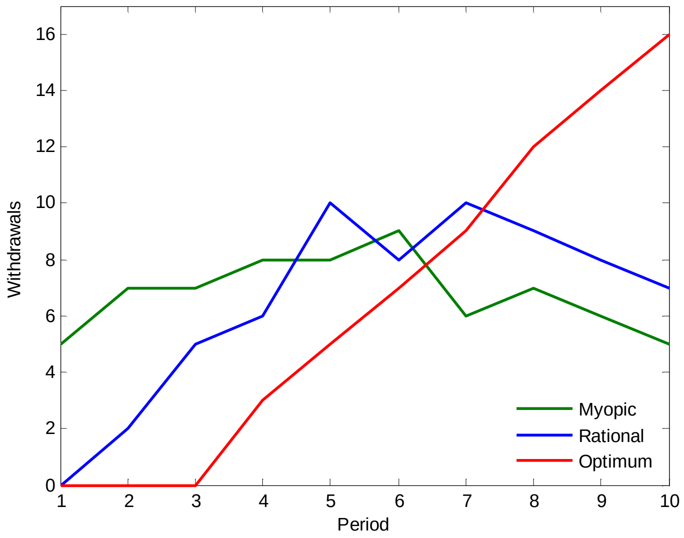

**Figure 3: Predictions of the AFT treatment.**

At least two independent groups of 5 subjects participated in each session. Subjects were assigned to separate boxes on a random basis. Communication was not allowed. At the beginning of a session, subjects first read individually the paper instructions, which were read aloud by an assistant after individual reading. Understanding was checked individually by a questionnaire[11]. No practice rounds were performed.

In each session, subjects participated in four repetitions of a ten-period dynamic game. We called this repetitions series 1, 2, 3 and 4. Subjects were given a show-up fee that was calculated to cover eventual losses. Prior to series 1, subjects were assigned to groups of five players without being told the identity of the other group members. The composition of groups remained the same during the whole experimental session. The same treatment condition was kept during the four series.

### *3.3 Decision Setting*

In each period, subjects choose independently and simultaneously the amount of units to extract. Individual unit orders were restricted to values in the range[12] $[0,50]$. In every treatment subjects disposed of two tables. The first table shows the return of various combinations of the available units in the account and unit orders (in the allowable range). Since we could not provide a complete table for all possible combinations, subjects were given a partial table as well as the formulae that were used to calculate the profit. The second table indicated the target of each period: the targeted stocks for the AFT treatment, and the individual extractions cut-off levels for the FT and MFI treatments. Moreover, in the FT treatment an additional table was provided showing the lump-sum penalties. Profits and penalties were expressed in “experimental points”, and subjects were aware of the conversion rate of points into Euros.

The size of the group and the profit function were common knowledge. At the beginning of each period, subjects were informed of their accumulated wealth and of the available units in

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[11] During the questionnaire filling subjects were allowed to ask questions individually to the assistants.

[12] Even if unit orders were not restricted to be integers, all participants have ordered integer amounts.

the account. After each decision period subjects were informed about their own profits for that period. A "summary table" of the series was available, with information about previous periods' accumulated wealth, net return, unit order, and the available units in the account.

## 4. Results

We run two sessions by treatment, involving the participation of 15 subjects each, excepting one session of the MFI treatment where only 10 subjects participated. Data of a total of 23 groups and 92 series (at the group level) were collected.

We call "unconditional benchmarks" the predictions described in figures 1, 2 and 3 because they rely on the common assumption that each subject behaves as predicted. As current decisions depend on the actual history of the game which can differ from the predicted path, new benchmark outcomes (depending on history) must be calculated. We call them "conditional benchmarks".

We first analyze the fitting of individual data to the benchmarks. This allows us to appropriately perform afterwards the assessment of the policy instruments efficiency. Under non optimal policy instruments, alternative behavioural assumptions (rational, myopic and optimum) lead to different predictions. To assess correctly the efficiency of a policy the population type must be known.

Tables 2 to 5 show the mean squared deviation (MSD) of individual data with respect to the unconditional benchmarks and in brackets the limits of the bootstrap intervals at 95% of confidence (if the intervals overlap the differences are not significant at the 5% significance level). The MSD of individual data with respect to the conditional benchmarks are shown on the right side of each table.

$$MSD = \sum_t \sum_i \left( y_{i,j}^{t} - y_{i,j}^{t\ e} \right)^2 \Big/ N \qquad (11)$$

Figures 4 to 7 plot the mean withdrawals with their bootstrap intervals at 95% of confidence and the conditional predictions of the theoretical strategies for each policy treatment respectively, as well as the mean withdrawals of the *laissez faire* treatment.

### *4.1 Comparison of behavioural hypotheses*

**RESULT 1**: In the *laissez-faire* treatment the myopic strategy is the best fitting strategy.

As can be seen from Table 2, the optimum strategy MSD with respect to the unconditional benchmark is significantly the largest one. Whilst the unconditional MSD does not allow distinguishing between the rational and the myopic behaviours, the MSD with respect to the conditional benchmarks indicates that the myopic strategy is the best fitting one. The conditional MSD of the myopic strategy is significantly lower than the rational strategy one (p-value = 0.0656; Friedman test). As shown in Figure 4, the mean extraction path is significantly lower than the myopic conditional benchmark and significantly higher than the rational conditional benchmark. Thus, mean extractions seem to back a mixed population of myopic and rational agents. However, until period seven the mean extraction path resembles rather to the myopic benchmark than to the rational one, thereafter we are unable to distinguish between these strategies. Detailed analysis on individual extractions must to be performed to clarify this point.

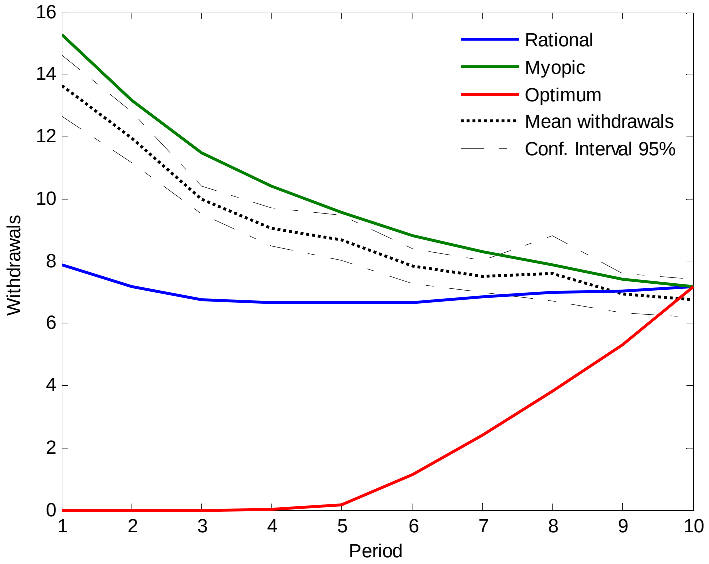

**Figure 4 : Mean withdrawals versus conditional benchmarks for the LF treatment.**

| LF treatment | | | | | | |
|---|---|---|---|---|---|---|
| | **Unconditional benchmarks** | | | **Conditional benchmarks** | | |
| **Strategy** | **Rational** | **Myopic** | **Optimum** | **Rational** | **Myopic** | **Optimum** |
| **Mean**<br>[95% intervals] | | | | | | |
| **Series** | | | | | | |
| **1** | 375.51<br>[197.16  586.51] | 382.91<br>[200.59  596.89] | 1010<br>[797.93 1265.6] | 440.9 | 381.4 | 1046.6 |
| **2** | 191.19<br>[81.02  215.89] | 150.65<br>[82.43  229.62] | 744.86<br>[686.68  807.48] | 213.9 | 181.4 | 764.9 |
| **3** | 188.89<br>[62.14  360.24 | 189.5<br>[65.84  360.81] | 849.5<br>[690.27 1045.13] | 286.2 | 200.2 | 894.2 |
| **4** | 65.11<br>[31.22  119.67] | 63.49<br>[31.08  112.04] | 746.11<br>[668.16  843.21] | 154.4 | 70.8 | 750.3 |
| **Global Mean**<br>[95% intervals] | **193.01**<br>[128.67  264.53] | **196.64**<br>[134.6  268.85] | **837.62**<br>[759.32  926.16] | **273.84** | **208.44** | **864.01** |

**Table 2: Mean Squared Deviation for the LF treatment.**

**RESULT 2**: In the *flat tax* treatment any benchmark successfully explains the data.

Inspection of Table 3 reveals that no significant differences exist between the rational and the myopic strategy as measured by MSD with respect to the unconditional benchmarks. Besides that the myopic strategy shows the lower MSD with respect to the conditional benchmark, we cannot conclude that it is the best fitting one. As shown in Figure 5, mean withdrawals are significantly different compared to the myopic conditional benchmark until period 8. In the later periods they remain above the rational conditional benchmark, but the difference between the benchmarks are not sufficient to conclude that the myopic strategy better fits the data.

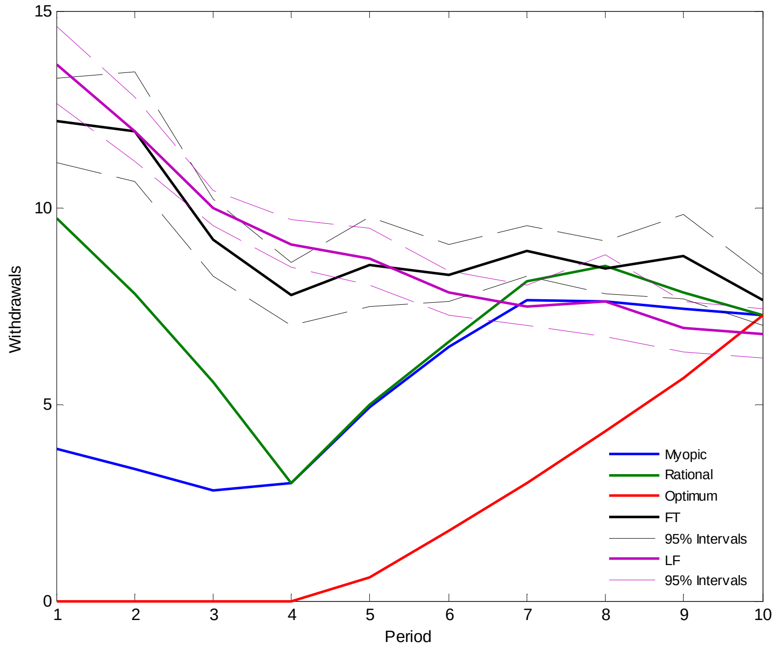

**Figure 5 : Mean withdrawals in LF and FT treatments versus FT conditional benchmarks.**

| FT treatment | | | | | | |
|---|---|---|---|---|---|---|
| | **Unconditional benchmarks** | | | **Conditional benchmarks** | | |
| **Strategy** | **Rational** | **Myopic** | **Optimum** | **Rational** | **Myopic** | **Optimum** |
| **Mean**<br>[95% intervals] | | | | | | |
| **Series** | | | | | | |
| **1** | 1164.69<br>[728.1  1654.7] | 997.53<br>[591.4  1444.5] | 1584.27<br>[1072.5  2167.5] | 1442.1 | 1249.8 | 1840.6 |
| **2** | 343.64<br>[245.57  475.09] | 226.74<br>[162.88  317.68] | 692.05<br>[539.78  876.73] | 370.7 | 249.5 | 708.8 |
| **3** | 288.57<br>[227.19  362.52] | 177.11<br>[132.67  235.03] | 621.97<br>[513.09  738.56] | 310.7 | 184.6 | 662.1 |
| **4** | 262.04<br>[225.69  304.34] | 147.74<br>[122.18  177.31] | 589.5<br>[512.41  672.87] | 295.5 | 173.0 | 638.4 |
| **Global Mean**<br>[95% intervals] | **514.73**<br>[405.12  645.54] | **387.28**<br>[285.73  504.38] | **871.95**<br>[734.5  1032.4] | **604.7** | **464.2** | **962.5** |

**Table 3: Mean Squared Deviation for the FT treatment.**

**RESULT 3**: In the *ambient flat tax* treatment the myopic strategy is the best fitting strategy.

Whilst the MSD with respect to the unconditional benchmarks indicates that the optimum strategy does not explain mean extractions, we cannot identify the best fitting among the two remaining strategies with this criterion. Nevertheless, the myopic conditional benchmark is the best fitting strategy as measured by the MSD with respect to the conditional benchmarks (p-value = 0.0163; Friedman test). Figure 6 shows that the difference between the myopic prediction and the mean withdrawals is significant until period 6. Besides, the mean extractions trajectory seems to follow the myopic trajectory.

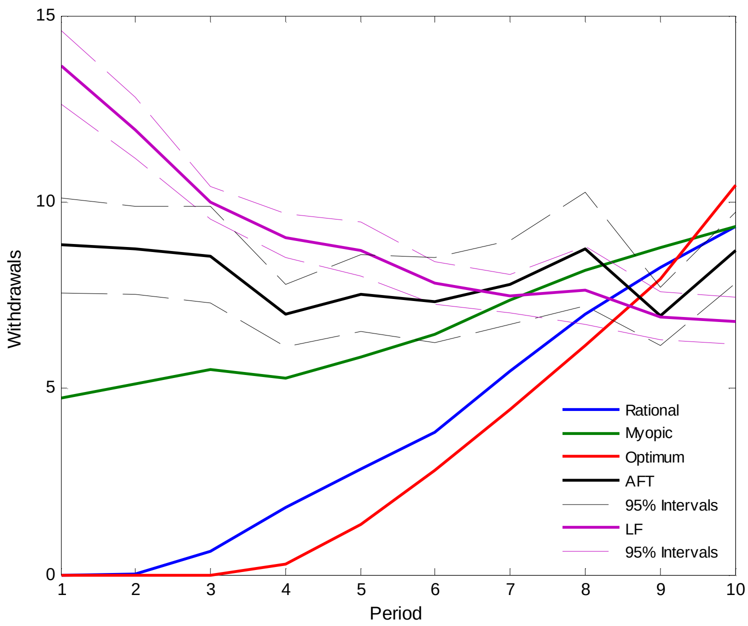

**Figure 6 : Mean withdrawals in LF and AFT treatment versus AFT conditional benchmarks.**

| | AFT treatment | | | | | |
|---|---|---|---|---|---|---|
| | **Unconditional benchmarks** | | | **Conditional benchmarks** | | |
| **Strategy** | **Rational** | **Myopic** | **Optimum** | **Rational** | **Myopic** | **Optimum** |
| **Mean**<br>[95% intervals] | | | | | | |
| **Series** | | | | | | |
| **1** | 677.61<br>[487.23  868.23] | 706.34<br>[516.51  902.13] | 1082.6<br>[894.6  1286.3] | 1136.6 | 870.9 | 1137.3 |
| **2** | 740.23<br>[503.07  993.97] | 781.89<br>[536.55  1030.2] | 1100.83<br>[807.31  1435.6] | 1066.3 | 850.3 | 1095.2 |
| **3** | 476.49<br>[322.09  708.4] | 532.91<br>[375.88  759.56] | 686.06<br>[485.62  970.24] | 666.5 | 519.6 | 696.8 |
| **4** | 285.97<br>[202.2  374.1] | 323.20<br>[232.7  419.88] | 655.39<br>[545.28  780.07] | 597.4 | 378.4 | 624.0 |
| **Global Mean**<br>[95% intervals] | **545.07**<br>[453.1  642.09] | **586.08**<br>[493.16  681.26] | **881.22**<br>[768.24  995.99] | **866.7** | **654.8** | **888.3** |

**Table 4: Mean Squared Deviation for the AFT treatment.**

**RESULT 4**: In the *mixed flat instrument* treatment the myopic and the rational strategies are equally well fitting the data.

Likewise in the treatments analysed previously, the optimum strategy's MSD with respect to the unconditional benchmark is significantly the largest one. However, under MFI neither the unconditional MSD nor the conditional MSD allows us to point out which strategy, myopic or rational, better explains the data (p-value = 0.1495; Friedman test). However, figure 7 clearly shows that mean withdrawals are significantly similar to the myopic benchmark, excepting in periods where the myopic and the rational conditional predictions overlap, i.e. periods 4, 5 and 6. This may suggests that mean withdrawals are generated by a mix of rational withdrawers who reacted to the instrument as expected and withdrawers who ignored the instrument.

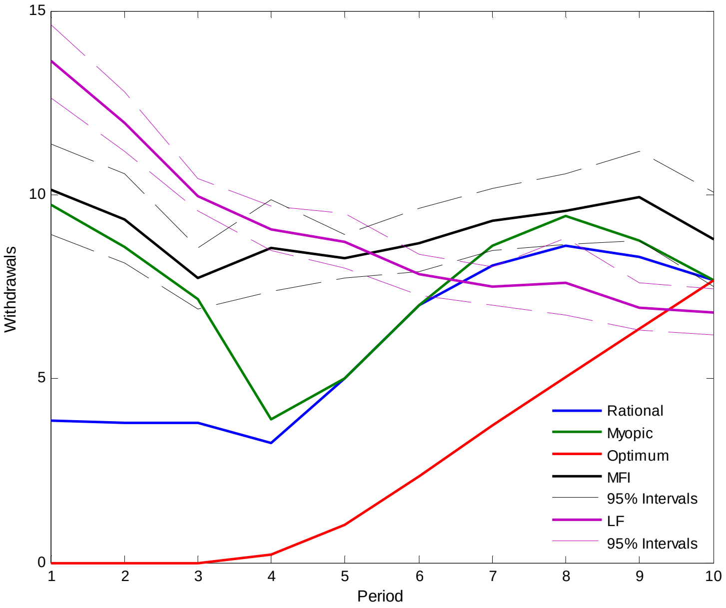

**Figure 7 : Mean withdrawals in LF and MFI treatment versus MFI conditional benchmarks.**

| | Treatment MFI | | | | | |
|---|---|---|---|---|---|---|
| | Unconditional benchmarks | | | Conditional benchmarks | | |
| **Strategy** | **Rational** | **Myopic** | **Optimum** | **Rational** | **Myopic** | **Optimum** |
| **Mean**<br>[95% intervals] | | | | | | |
| **Series** | | | | | | |
| **1** | 520.86<br>[324.11 729.91] | 415.18<br>[238.15 597.63] | 869.29<br>[640.3 1145.0] | 591.3 | 466.2 | 962.4 |
| **2** | 604.14<br>[333.79 903.32] | 554.65<br>[266.57 872.67] | 855.09<br>[602.5 1133.7] | 781.3 | 718.0 | 1117.8 |
| **3** | 480.25<br>[253.84 739.61] | 387.58<br>[193.31 615.24] | 805.29<br>[527.6 1135.6] | 525.1 | 431.8 | 872.0 |
| **4** | 217.82<br>[170.04 274.75] | 195.46<br>[147.60 246.92] | 444.43<br>[343.34 555.81] | 246.8 | 228.5 | 519.3 |
| **Global Mean**<br>[95% intervals] | **455.77**<br>[351.5 579.1] | **388.22**<br>[286.75 508.64] | **743.53**<br>[626.67 880.84] | **536.1** | **461.1** | **867.9** |

**Table 5: Mean Squared Deviation for the MFI treatment.**

### *4.2 Instrument efficiency assessment*

**RESULT 5**: The AFT and MFI policies significantly move extractions towards the optimum unconditional benchmark with respect to the *laissez-faire* observed extraction path.

The conditional benchmarks converge to the same extraction level in the last period. Therefore the incentive instruments must achieve a reduction of extractions in early periods of the temporal horizon to be effective. The withdrawal trajectory of those instruments that succeed have a positive slope, and cross the LF mean withdrawals trajectory in the same way that the myopic prediction crosses the optimum trajectory in Figure 1.

Figure 5 shows that the FT does not achieve a significant shift of the extraction trajectory towards the optimum. Although the trajectories cross each other the differences are not significant except in period 9. Additionally, the MSD of the optimum strategy under the flat tax (Table 3) does not show any significant reduction with respect to the LF treatment (Table 2). From Figure 7 it can be seen that the MFI accomplishes a significant move towards the optimum unconditional benchmark; the trajectories clearly cross each other. However, this is not supported by the comparison of the MSD of the optimum strategy with the LF treatment. The AFT achieves the most important extraction reduction in early periods (Figure 6), but extractions remain stable over the horizon.

Cheating could be an explanation for the poor performance of the FT instrument in moving the extraction trajectory toward the optimum. Under AFT cheating is irrelevant since there are not withdrawals declarations, and in the MFI the group fraud is always detected, though it is not always individually punished. However, in the FT the random audit the agents may underestimate the expected penalty and be encouraged to cheat.

**RESULT 6**: In the FT treatment, cheating explains the deviations with respect to the myopic conditional benchmark.

In order to support result 6, let us define a new extraction path generated by a population containing a mix of "cheaters" and compliant agents. In a given period we assume that a cheating agent declares zero extraction, but withdraws from the account as if the tax rate was null. On the other hand, a compliant agent behaves according to the myopic conditional prediction. The mix changes over time since a compliant agent might become a cheater, while a cheater might become compliant. Expression (12) describes the extraction path generated by the mixed population. We call it "X prediction" thereafter. Note that if the population is fully compliant the "X prediction" overlaps with the myopic conditional benchmark.

$$y_x^t = \gamma^t \cdot y_m^t\left(S^t,\tau^t\right) + \left(1-\gamma^t\right)\cdot y_m^t\left(S^t,0\right) \tag{12}$$

Where $\gamma^t$ is the compliance rate in period *t*, $y_m^t\left(S^t,\tau^t\right)$ is the myopic conditional benchmark given the stock $S^t$ and the tax rate $\tau^t$, and $y_m^t\left(S^t,0\right)$ is the myopic conditional benchmark of the *laissez faire* situation.

Figure 8 plots the mean extractions, the myopic conditional benchmark, and the "X prediction" defined above. As can be seen the "X prediction" fits quite well the mean extractions in the FT. It does not differ significantly from the mean extractions except in the first series of groups 1, 5 and 6.

**RESULT 7**: The contrast between the FT and the MFI policies reveals that the collective penalty achieves higher compliance than the lump-sum penalty.

Figure 9 reports the mean compliance rates, defined as the ratio of the declared to the real extractions, and the bootstrap intervals at 95% of confidence for the FT and MFI for each period. Significant differences are observed for periods 1, 4, 6, 7, 9 and 10.Thus, results 5, 6 and 7 suggest that compliance is a crucial determinant of the effectiveness of a policy instrument.

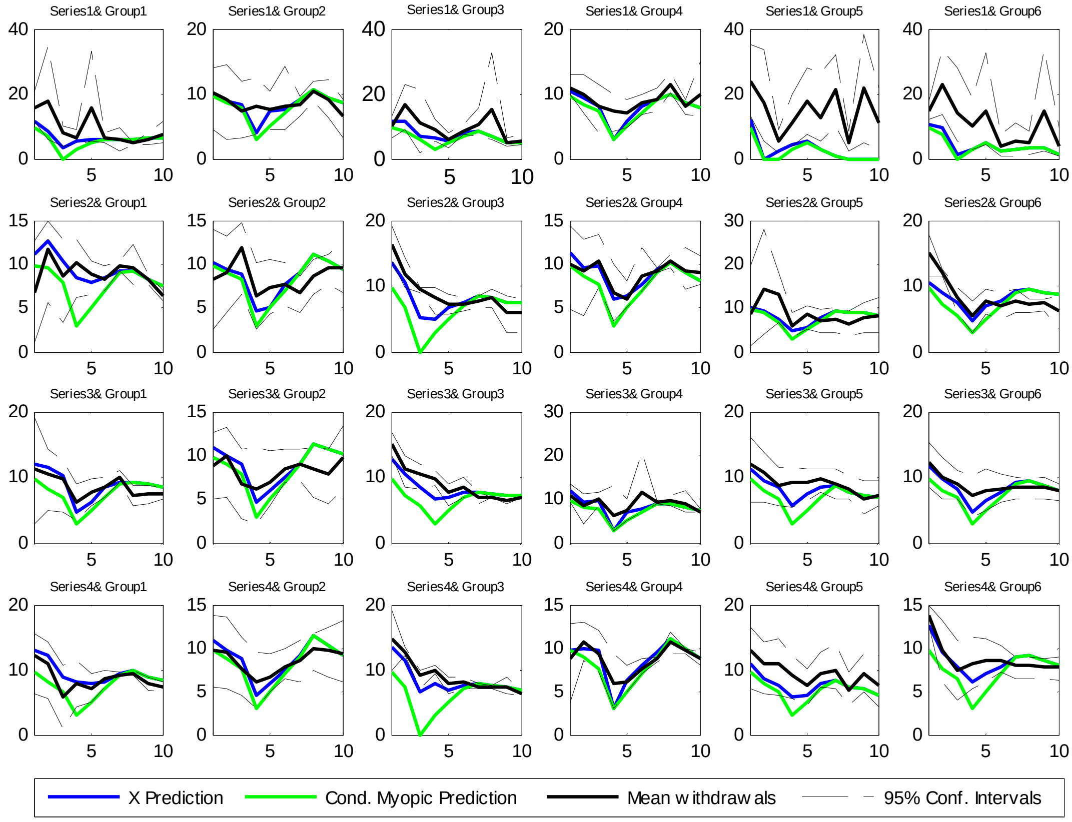

**Figure 8 : Mean extractions, myopic conditional benchmark and X Prediction by group and series for the FT treatment.**

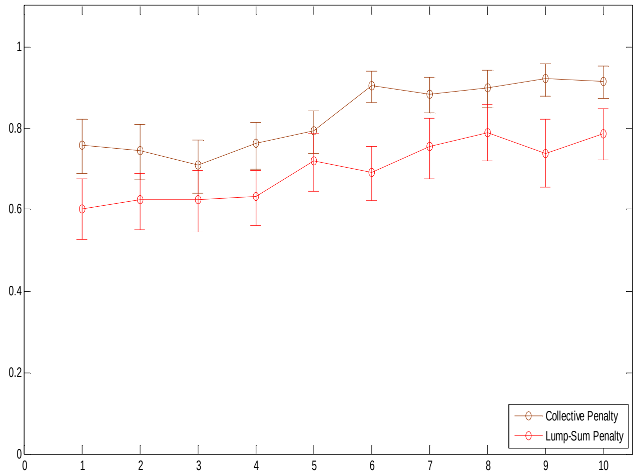

**Figure 9 : Mean compliance rate and 95% confidence bootstrap intervals for FT and MFI treatments.**

As a general result the tested policies were unsuccessful. The MSD with respect to the optimum unconditional benchmark remains very high in every policy treatment and takes similar values to those of the LF treatment. Besides, their effectiveness can be assessed and compared.

We perform comparisons of instruments by using an effectiveness indicator. Deviations of the observed extractions with respect to the optimum trajectory cannot be directly used as a measure of effectiveness because conditional predictions differ depending on the evolution of the stock. Therefore, we normalize the deviation by the conditional prediction of the "strength of the social dilemma" (SSD), which is measured as the absolute value of the difference between the optimum unconditional prediction (the target trajectory) and the myopic/rational conditional predictions. The larger the SSD the higher will be the weight in terms of effectiveness of each unit of differential reduction. The indicator of ineffectiveness is given by:

$$\begin{aligned} &\text{Myopic SSD} \qquad \sum_t \sum_i \left( \frac{\left|y^{t*} - y_m^t\left(S^t\right)\right|}{\left|y_i^t - y^{t*}\right|} \right) \Bigg/ N \cdot T \\ &\text{Rational SSD} \qquad \sum_t \sum_i \left( \frac{\left|y^{t*} - y_r^t\left(S^t\right)\right|}{\left|y_i^t - y^{t*}\right|} \right) \Bigg/ N \cdot T \end{aligned} \tag{13}$$

Where $y_i^t, y_m^t, y_r^t, y^{t*}$ are respectively, the observed extractions of subject *i*, the myopic and rational conditional benchmarks, and the optimum unconditional benchmark.

**RESULT 8**: Under the assumption of myopic behaviour for all players, the most effective instruments are the MFI and the FT.

On the basis of the effectiveness indicator for a myopic population, we reject the null hypothesis that all samples are drawn from the same distribution[13] (p-value 0.000; Friedman test). The effectiveness mean indicator of the *mixed flat instrument* is equal to 0.1642, which is significantly higher than the effectiveness mean indicator of the *ambient flat tax,* equal to 0.0647 (p-value = 0.000; Friedman test). No significant difference exist with the *flat tax*, the effectiveness indicator being equal to 0.1523 (p-value = 0.4233; Friedman test). Additionally, the AFT is significantly less effective than the FT (p-value = 0.000; Friedman test).

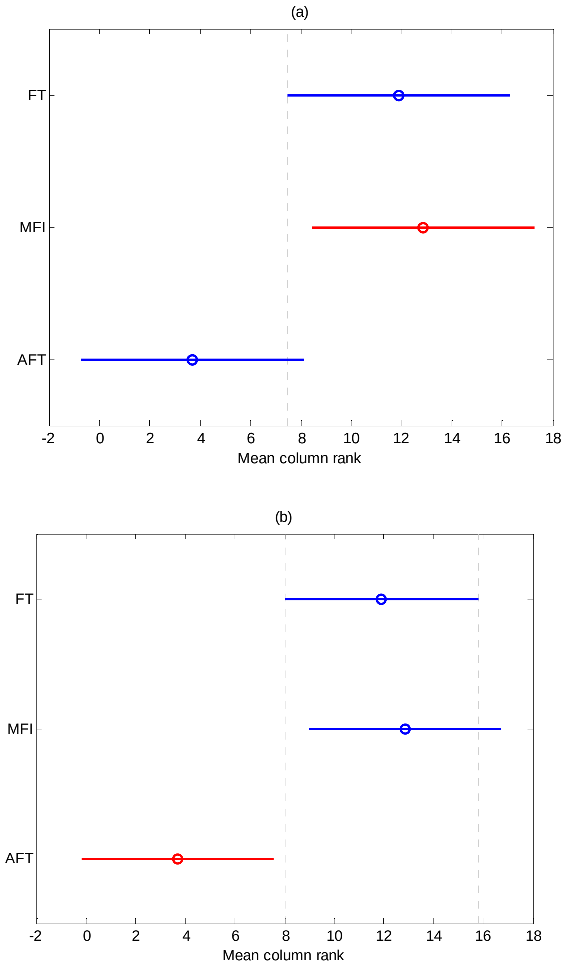

**Figure 10 : Policy effectiveness comparisons; myopic population.**

In order to avoid excessive inference errors, we carry out a multi-comparison test based on Tukey's honestly significant difference criterion[14]. Panel (a) of Figure 8 shows that the mean rank of the AFT is significantly smaller than for MFI (5% significance level), but there is no significant difference between AFT and FT. However at the 10% significance level we found the result of the individual comparisons described in the previous paragraph (panel (b) of

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[13] For the MFI we have only 5 independent groups. Since the Friedman test requires balanced samples we duplicated randomly one group of the MFI treatment. In this case samples contain 24 observations: 4 series per group and 6 groups in each treatment.

[14] The test was implemented by the *multcompare* function of the Matlab 6.5 Statistical toolbox.

Figure 5). Both panels of Figure 8 also show that FT is less effective than MFI. This is backed by the MSD observation that the MFI policy is closer to the optimum than the FT policy (Tables 5 and 3, respectively).

Result 8 contrasts sharply with result 5. This is due to the predicted differences in the strength of the social dilemma (SSD) that modifies the weighting of the deviations in the effectiveness indicator (equation 13). For example, in the case of a myopic population the SSD is given by the difference between the myopic conditional benchmark and the optimum unconditional benchmark. From figures 6 and 7 it can be seen that in period 1 the SSD under FT and MFI is twice the SSD of AFT. Consequently, under the assumption of a rational population, the policy effectiveness comparison may provide different results because the SSD predicted values for each policy differs compared to the myopic population case.

**RESULT 9**: Under the assumption of rational behaviour for all players, all policies are equally effective.

As for the case of a myopic population, we reject the null hypothesis that all samples are drawn from the same distribution (p-value = 0.0731; Friedman test). The effectiveness mean indicator of the MFI is equal to 0.1634 and is significantly higher than the effectiveness mean indicator of the AFT, which is equal to 0.1271 (p-value = 0.0306; Friedman test). The *flat tax* effectiveness mean indicator is equal to 0.1508 and does not show a significant difference with the MFI indicator (p-value = 0.5218; Friedman test) nor with the AFT indicator (p-value = 0.1093; Friedman test).

In contrast to the myopic case, the AFT effectiveness indicator is much higher here. The multi-comparison test does not show any significant difference in the effectiveness mean indicator (Figure 9). Thus, the results of the individual comparisons are not supported preventing us to point out the most effective policy.

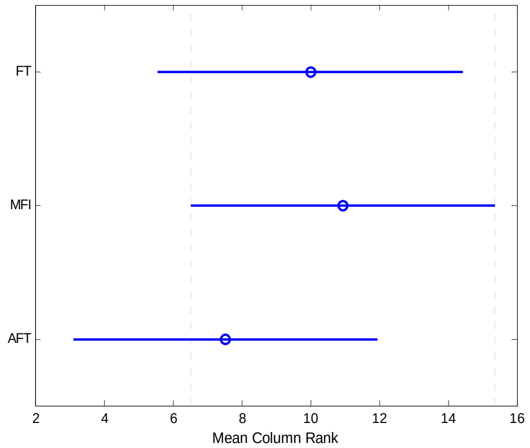

**Figure 11 : Policy effectiveness comparisons; rational population.**

This divergence highlights the importance of the behavioural rules which characterise the target population for the design and evaluation of incentive policy instruments. Our instruments are not individual-specific since they are uniformly applied to the entire population. Our results clearly show that the predicted efficiency differs sharply depending on the population type. Thus, the evaluation of an incentive policy performance may result in opposite conclusions depending on what we expect from an instrument.

**RESULT 10**: The *flat tax* is the most efficient policy and the *ambient flat tax* is the less efficient, in gross and net terms.

Table 6 shows the efficiency of each treatment. Gross efficiency is measured as the ratio of the accumulated wealth at the end of the game and the optimum strategy wealth (unconditional prediction). The net efficiency is measured in the same way that the gross efficiency but the tax and penalty payments are deduced from the accumulated wealth.

On the basis of gross efficiency FT is close to the LF. Combined to result 2, it seems that the FT instrument was completely ignored by the subjects. But result 8 does not support this conclusion. Paradoxically, the instruments that were most successful to curb the extraction path towards the optimum path, the MFI and the AFT as stated in result 5, are the less efficient ones. In our dynamic game stock saving implies forgone earnings that must be "cashed" in future periods by extracting the optimal quantities, otherwise losses become significant. This is likely to have happened under the AFT and MFI instruments. Figures 6 and 7 show that the resource stock was respectively under and over exploited in the final periods with respect to predictions. Thus, care must be paid in implementing time inconsistent instruments, since early deviations from predictions alter the incentives set by each policy, either encouraging non optimal behaviour or just confusing subjects with distorted signals. Anyhow, deeper analysis on individual decisions must be performed to assess more accurately the impact of time inconsistency.

All policy instruments performed quite badly in terms of net efficiency (Table 6). The large differences in the net efficiency just indicate the strength of audit and penalty systems to assure compliance.

| | | Global mean | Myopic prediction |
|---|---|---|---|
| Treatments<br>-<br>Gross efficiency<br>(Net efficiency) | LF | 47.82% | 51.8% |
| | FT | 41.71%<br>(3.25%) | 79.2%<br>(62.79%) |
| | MFI | 30.76%<br>(-27.1%) | 79.2%<br>(62.79%) |
| | AFT | 20.88%<br>(-99.52%) | 81.6%<br>(-20.4%) |

**Table 6 : Gross and net mean efficiency.**

## 5. Conclusion

In this paper we tested experimentally three alternative non optimal policies to cope with dynamic externalities. We considered policies designed for managing the exploitation of a renewable common-pool resource when the time horizon is finite and individual withdrawals are unobservable by the regulator.

In a dynamic framework, policy parameters must change from one period to the other to adapt to the resource state and to the remaining time. In order to correctly internalize the externalities, the tax rate, the penalties, and the targets need to be adjusted to the new state of the resource. Because the practical implementation of such flexible policies is generally unfeasible, because of technical and ethical constraints, we considered that the regulator is restricted to implement 'fixed' non optimal instruments, i.e. policy parameters remain fixed all along the temporal horizon. While fix instruments are time inconsistent, they still may be able to implement the first best extraction path.

We compared three alternative non optimal instruments: (*i*) a fix rate tax on declared extractions with a compliance monitoring mechanism (*flat tax*, FT treatment), (*ii*) an ambient tax with fixed tax rates and targets (*ambient flat tax*, AFT treatment), and (*iii*) a mixed instrument (*mixed flat instrument*, MFI treatment) combining the two previous instruments. All three instruments share the particularity that if extractions are lower or equal to an exogenous target, the tax rate is null. While the targets are set at the individual level for FT and MFI, they are set at the group level for AFT. FT and MFI differ with respect to the compliance monitoring mechanism. Under FT random auditing is implemented to detect cheaters who must pay their tax debt and a lump-sum penalty. Under MFI a collective penalty is levied if total declared extractions differ from the total extraction observed by the regulator. Random controls are implemented to track for cheating appropriators who must pay their tax debt and the collective penalty while the compliant appropriators are freed of paying the collective penalty.

The AFT and MFI succeed in moving significantly the mean extraction path towards the optimum path, compared to the *laissez faire* mean trajectory. On the contrary, the FT instruments had no impact on subjects' decisions, since the rate of compliance is very low under this instrument. Actually, the collective penalty under the MFI achieved higher compliance than random audit with lump-sum penalty implemented in the FT. Anyhow compliance achieved by the collective penalty remains under the prediction (no cheating).

Additionally, we compared the instruments' effectiveness in approaching the optimum trajectory, on the basis of an indicator that takes into account the "strength of the social dilemma" (SSD). Roughly speaking, the SSD indicator corrects the difference between the observed trajectory with the instrument and the target trajectory by a measure of distance between the predicted trajectory with the instrument and the target trajectory. Two distinct comparisons were performed, corresponding respectively to a myopic behavioural hypothesis and to a rational behavioural hypothesis. No significant difference in effectiveness between instruments was found under the rational behavioural hypothesis. However, under myopic behaviour, AFT is the least effective instrument, in sharp contrast with the evidence exposed previously. This conclusion is attributable to the predicted differences in the strength of the social dilemma (SSD) that affects the weighting of the deviations in the effectiveness indicator. The divergence highlights the importance of the behavioural rule which characterises the target population for the design and evaluation of incentive policy instruments. Our results clearly show that the predicted efficiency is strongly affected by the behavioural assumption about the relevant population of players. We conclude that the expected performance of an instrument is strongly dependent on the agents' behaviour.

From a practical point of view, our results suggest that the implementation of time inconsistent policy-instruments must be made very cautiously. We found that that the most successful instruments for shifting the extraction path towards the optimum path (i.e. MFI and

AFT) are the less efficient ones. In the dynamic game we have tested, a stock saving implies forgone earnings that must be "cashed" in future periods by extracting the optimal quantities, otherwise losses will become significantly high. A policy that does not give enough incentives to cash the fruits of previous savings will be inefficient. Consequently, our results strongly suggest that the design and implementation of time inconsistent instruments demand great vigilance as early deviations from predictions alter the incentives introduced by each policy, encouraging thereby non optimal behaviour or just confusing agents with distorted signals.

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## Acknowledgments

We would like to thank Mabel Tidball, Marielle Montginoul and Bertrand Aunay for their stimulating discussions and valuable comments as well as the participants of the SysCoLag seminars. We acknowledge the Languedoc-Roussillon Region and IFREMER for financial support.

## Appendix: Equilibrium Derivation

In this appendix we show how the Rational, the Myopic and the Optimum outcomes are derived.

***Rational outcome***

The optimisation horizon is finite and known with certainty. Each appropriator calculates a feedback strategy, supposing that there are *N-1* other appropriators behave in the same manner (Equation A2.4). Each solves the program:

$$\max_{y_i^t} V_i^t(y^t, S^t)$$

$$\text{s.t.} \quad y^t \geq 0 \qquad i = 1,\ldots,N \qquad \text{Program (A)}$$

$$S^t - Y^t \geq 0$$

Where,

$y^t = (y_1^t,\ldots,y_i^t,\ldots,y_n^t)$,

$$V_i^t(y^t, S^t) = EU_i^t(y^t, S^t) + \sum_{s=t+1}^{T} \rho^{s-t} \cdot EU_i^{*s}(y_r^{*s}, S^s) \qquad i = 1,\ldots,N$$

$\rho \in (0,1)$ is the discount rate, and $y_r^{s*}(S^s)$ is the optimal feedback for period *s* resulting from the solution of the equation system constituted of the program (A)'s *N* F.O.C. in period *s*.

$$y^t(S^t) = C^t \cdot \left[A^t \cdot E^t + l \cdot r \cdot (G^t + F^t)\right] \qquad \text{A.1}$$

Where,

$l = f + \phi$,

$$A^t = a - P + l \cdot S^t, \qquad \text{A.1.1}$$

$$E^t = 1 + \left(\frac{1}{C^t} - D\right)\frac{1}{l \cdot n}, \; C^T = 1/D, \; E^T = 1, \qquad \text{A.1.2}$$

$$D = 2b + (n+1)z, \qquad \text{A.1.3}$$

$$\begin{aligned} C^t = 1 \Big/ \Big\{ & D - nl \sum_{\tau=t+1}^{T} \rho^{\tau-t} \Big[ l\cdot E^{\tau} \cdot C^{\tau} \Big[ 1+\sum_{s=t+1}^{\tau-1}\prod_{q=s}^{\tau-1}\big(-l\cdot E^{q}\cdot C^{q}\big)\Big]\cdot\Big[2\cdot\Big(1-l\sum_{s=t+1}^{\tau-1}E^{s}\cdot C^{s}\cdot\Big[1+\sum_{e=t+1}^{\tau-2}\prod_{q=e}^{\tau-2}\big(-l\cdot E^{q}\cdot C^{q}\big)\Big]\Big) \\ & - D\cdot E^{\tau}\cdot C^{\tau}\Big[1+\sum_{s=t+1}^{\tau-1}\prod_{q=s}^{\tau-1}\big(-l\cdot E^{q}\cdot C^{q}\big)\Big]\Big]\Big]\Big\}, \end{aligned} \tag{A.1.4}$$

$$G^t = \big(E^t - 1\big) - \rho\cdot l\cdot C^{t+1}\big(G^{t+1}+F^{t+1}\big)\cdot\big[E^{t+1}\cdot D-1\big],\ G^T = 0\,, \tag{A.1.5}$$

$$\begin{aligned} F^t = & -\sum_{\tau=t+2}^{T}\rho^{\tau-t}\Big\{ l\cdot E^{\tau}\cdot C^{\tau}\Big[1+\sum_{s=t+1}^{\tau-1}\prod_{q=s}^{\tau-1}\big(-l\cdot E^{q}\cdot C^{q}\big)\Big]\cdot\Big[\big[\tau-(t+1)\big]\cdot\big(1-D\cdot E^{\tau}\cdot C^{\tau}\big)-D\cdot C^{\tau}\big(F^{\tau}+G^{\tau}\big)- \\ & -\big(1-D\cdot E^{\tau}\cdot C^{\tau}\big)\cdot\Big[nl\sum_{e=1}^{\tau-1}\Big[1+\sum_{s=t+1}^{e-1}\prod_{q=s}^{e-1}\big(-l\cdot E^{q}\cdot C^{q}\big)\Big]\cdot\big[C^{e}\big(F^{e}+G^{e}\big)+E^{e}\cdot C^{e}\cdot\max[0,e-(t+1)]\big]\Big]\Big]+ \\ & \quad +l\cdot\Big(1-l\sum_{h=t+1}^{\tau-1}E^{h}\cdot C^{h}\cdot\Big[1+\sum_{k=t+1}^{h-1}\prod_{q=k}^{h-1}\big(-l\cdot E^{q}\cdot C^{q}\big)\Big]\Big)\cdot\Big[\big[\tau-(t+1)\big]\cdot E^{\tau}\cdot C^{\tau}+C^{\tau}\big(F^{\tau}+G^{\tau}\big)- \\ & \quad -nl\cdot E^{\tau}\cdot C^{\tau}\sum_{e=1}^{\tau-1}\Big[1+\sum_{s=t+1}^{e-1}\prod_{q=s}^{e-1}\big(-l\cdot E^{q}\cdot C^{q}\big)\Big]\cdot\big[C^{e}\big(F^{e}+G^{e}\big)+E^{e}\cdot C^{e}\cdot\max[0,e-(t+1)]\big]\Big]\Big\}, \end{aligned} \tag{A.1.6}$$

$$F^T = F^{T-1} = 0\,.$$

$$C^t = 1 \Big/ \Big\{ D - nl \sum_{\tau=t+1}^{T} \rho^{\tau-t} \Big[ nl \cdot E^{\tau} \cdot C^{\tau} \Big[ 1 + \sum_{s=t+1}^{\tau-1} \prod_{q=s}^{\tau-1} \big( -nl \cdot E^{q} \cdot C^{q} \big) \Big] \cdot \Big[ 2 \cdot \Big( 1 - nl \sum_{s=t+1}^{\tau-1} E^{s} \cdot C^{s} \cdot \Big[ 1 + \sum_{e=t+1}^{\tau-2} \prod_{q=e}^{\tau-2} \big( -nl \cdot E^{q} \cdot C^{q} \big) \Big] \Big)$$

$$- D \cdot E^{\tau} \cdot C^{\tau} \Big[ 1 + \sum_{s=t+1}^{\tau-1} \prod_{q=s}^{\tau-1} \big( -nl \cdot E^{q} \cdot C^{q} \big) \Big] \Big] \Big] \Big\} \qquad \text{A.3.7}$$

$$G^t = \big( E^t - 1 \big) - \rho \cdot nl \cdot C^{t+1} \big( E^{t+1} + F^{t+1} \big) \cdot \big[ E^{t+1} \cdot C^{t+1} \cdot D - 1 \big], \qquad \text{A.1.8}$$

$$F^t = - \sum_{\tau=t+2}^{T} \rho^{\tau-t} \Big\{ nl \cdot E^{\tau} \cdot C^{\tau} \Big[ 1 + \sum_{s=t+1}^{\tau-1} \prod_{q=s}^{\tau-1} \big( -nl \cdot E^{q} \cdot C^{q} \big) \Big] \cdot \big[ [\tau - (t+1)] \cdot \big( 1 - D \cdot E^{\tau} \cdot C^{\tau} \big) - D \cdot C^{\tau} \big( F^{\tau} + G^{\tau} \big) -$$

$$- \big( 1 - D \cdot E^{\tau} \cdot C^{\tau} \big) \cdot \Big[ nl \sum_{e=1}^{\tau-1} \Big[ 1 + \sum_{s=t+1}^{e-1} \prod_{q=s}^{e-1} \big( -nl \cdot E^{q} \cdot C^{q} \big) \Big] \cdot \big[ C^{e} \big( F^{e} + G^{e} \big) + E^{e} \cdot C^{e} \cdot \max[0, e - (t+1)] \big] \Big] \Big] + \qquad \text{A.3.9}$$

$$+ l \cdot \Big( 1 - nl \sum_{h=t+1}^{\tau-1} E^{h} \cdot C^{h} \cdot \Big[ 1 + \sum_{k=t+1}^{h-1} \prod_{q=k}^{h-1} \big( -nl \cdot E^{q} \cdot C^{q} \big) \Big] \Big) \cdot \big[ [\tau - (t+1)] \cdot E^{\tau} \cdot C^{\tau} + C^{\tau} \big( F^{\tau} + G^{\tau} \big) -$$

$$- nl \cdot E^{\tau} \cdot C^{\tau} \sum_{e=1}^{\tau-1} \Big[ 1 + \sum_{s=t+1}^{e-1} \prod_{q=s}^{e-1} \big( -nl \cdot E^{q} \cdot C^{q} \big) \Big] \cdot \big[ C^{e} \big( F^{e} + G^{e} \big) + E^{e} \cdot C^{e} \cdot \max[0, e - (t+1)] \big] \Big] \Big\}.$$

***Myopic outcome***

In the myopic behaviour case, the optimization horizon is just one period. Supposing that everybody behaves myopically, the myopic appropriator calculates a period's profit maximizing extraction taking the rules of his rivals as given:

$$\max_{y_i^t} \; EU\left(y^t, S^t\right)$$

$$\text{s.t.} \quad y^t \geq 0 \qquad i = 1,\ldots,N \qquad \text{Program (B)}$$

$$S^t - Y^t \geq 0$$

Each period withdrawals are represented by a function of the available stock that is invariant with time, $y_i\left(S^t\right)\ \forall i$, resulting from the solution of the equation system constituted of the program (B)'s *N* F.O.C.:

$$y_m^t\left(S^t\right) = \frac{a - p + l \cdot S^t}{2b + (n+1)z} = \frac{A^t}{D} \quad \forall t \qquad \text{A.2}$$

Note that the myopic optimal feedback is similar to the period *T* rational optimal feedback. Equation A.2 can be obtained from equations A.1 for null discount rate, $\rho = 0$.

***Optimum outcome***

In each period *t*, withdrawers behaves like a benevolent regulator, they maximise the sum of the joint profit from *t* until *T*:

$$\max_{y^t} \sum_{t=1}^{T} \sum_{i=1}^{N} V_i^{*t}(y^t, S^t)$$

$$\text{s.t.} \quad y^t \geq 0 \qquad \text{Program (C)}$$

$$S^t - Y^t \geq 0$$

where,

$y^t = (y_1^t, \ldots, \; y_i^t, \ldots, \; y_n^t)$,

$$V_i^{*t}(y^t, S^t) = EU_i^t(y^t, S^t) + \sum_{s=t+1}^{T} \rho^{s-t} \cdot EU_i^{*s}(y^{*s}, S^s) \qquad i = 1,\ldots,N$$

$\rho \in [0,1)$ is the discount rate, and

$$y^{*t} = \underset{(y_1^t,\ldots,y_i^t,\ldots,y_n^t)}{\arg\max} \sum_{s=t}^{T} \sum_{i=1}^{N} V_i^{*s}(y^{s*}, S^s)$$

Like in the rational outcome, each period extractions are, $y_i^{*t}$, are a function of the available stock and time (equations A.1). It is just needed to replace equations A.1.4 by A.3.7, A.1.6 by A.3.9, and A.1.3 par :

$$D = 2b + 2nz \qquad \text{A.3.1}$$

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(lxxxi) This paper was presented at the EAERE-FEEM-VIU Summer School on "Computable General Equilibrium Modeling in Environmental and Resource Economics", held in Venice from June 25th to July 1st, 2006 and supported by the Marie Curie Series of Conferences "European Summer School in Resource and Environmental Economics".

(lxxxii) This paper was presented at the Workshop on “Climate Mitigation Measures in the Agro-Forestry Sector and Biodiversity Futures”, Trieste, 16-17 October 2006 and jointly organised by The Ecological and Environmental Economics - EEE Programme, The Abdus Salam International Centre for Theoretical Physics - ICTP, UNESCO Man and the Biosphere Programme - MAB, and The International Institute for Applied Systems Analysis - IIASA.

(lxxxiii) This paper was presented at the 12th Coalition Theory Network Workshop organised by the Center for Operation Research and Econometrics (CORE) of the Université Catholique de Louvain, held in Louvain-la-Neuve, Belgium on 18-20 January 2007.

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