AN EXPERIMENTAL STUDY ON SUBSTITUTE COMMON-POOL RESOURCES IN A DYNAMIC FRAMEWORK: *THE AGRICULTURAL EXPLOITATION OF GROUNDWATER*

(Preliminary Version)

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February 2005

Abstract: Experimental research has shown that human subjects do not have a good perception of the future consequences of their current actions. One can therefore expect that in situations involving dynamic externalities, the outcome of individual decisions will be very inefficient. Static externalities in this kind of dynamic environment may enhance the perception of common property of the resource, leading to a more efficient exploitation. In order to evaluate this hypothesis, we compare the efficiency of the CPRs exploitation by studying an N-person discrete-time deterministic dynamic game of T periods fixed duration. The objective function is stage-additive and depends on a state variable, whose dynamic evolution is linked to past decisions of all players. The players have to decide whether to use a private good or, by paying a lump-sum fee, to extract on one of two imperfectly substitute Common-Pool Resources.
The observations are confronted to three benchmark outcomes corresponding to distinct behavioural assumptions: (*a*) sub-game perfection, (*b*) joint payoff maximization, and (*c*) myopic behaviour.

Key words: Common-Pool Resources, Dynamic Externalities, Survival Data, Proportional Hazard, Experiment.
JEL Classification: D9, D62, H23, H30.

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1. Introduction

Groundwater exploitation, like many other natural resources exploitation, generates negative *appropiation externalities* (Ostrom, Gardner et al. 1994). In particular, the current practice of groundwater exploitation in coastal zones, poses a dramatic common pool resource (CPR) dilemma, generating a major challenge for the sustainable development of these areas, and possibly catastrophic consequences. Notably, overexploitation of groundwater in these zones may lead to water resource degradation as consequence of salt water intrusion into the aquifer[1].

Many coastal zones are the result of thousands of years of deposit sedimentation that generated rich groundwater reservoirs. These reservoirs, settled in layers of different depths, are independent of each other in some areas, and represent therefore imperfect substitutes water resources for the end-users. The exploitation of a particular groundwater reservoir can therefore be considered as the result of a choice between substitute resources. Appropriators may prefer to exploit the CPR because they are unsatisfied with the exploitation of an outside option (e.g., surface water) because water quality is low, or because there is quantity rationing. For example, a farmer who pumps groundwater from a shallow layer may decide to drill more deeply to satisfy his/her irrigation water needs[2].

From a management perspective, the regulation of the exploitation of a multi-layer aquifer requires deep knowledge of the appropriators' and resource characteristics for the regulatory agency. Firstly, the externality generated by the exploitation of a particular layer does not equally affect all appropriators, but depends on which layer is being exploited by each appropriator. Secondly, because of different physical properties (size, substratum, limit and dynamic properties, etc.) appropriation externalities are specific to each layer, and are therefore more or less harmful to end-users. Moreover, since the links between the different layers may be quite intricate, the management of the aquifer can be quite complex. The case of the Roussillon coastal plane, a zone located in the Pyrénées-Orientales department (South of France), which is a good representative case of water problems faced in southern Europe, fairly shows the challenges that multilayer aquifers pose to water managers. In this region, water demand is satisfied by surface water and a two-layer local aquifer. The superficial layer has sea connections, meaning that overexploitation can generate sea water intrusion. The layers are naturally separated by an impermeable substratum. This independency can be broken by an overexploitation of the deep layer; the impermeable substratum could become locally permeable letting polluted water from the superficial layer percolate.

We have designed an experiment to study the appropriators' behavior in a situation where they have the choice between imperfectly substitutable resources[3]. The aim of the analysis is to evaluate the determinants of the resource choice and the efficiency of the exploitation in a dynamic framework. In a finite horizon dynamic game, individuals have two decisions to take in each period: (i) which of the three available resources to use, and (ii) the quantity to extract. A distinction is made between dynamic (time dependent) and static (time independent) externalities

[1] Many coastal aquifers in the world have suffered from this phenomenon (Giordana and Montginoul, 2005) and many others are at risk without an adapted management.

[2] This is also a typical situation for other CPR as fisheries. The size of ships allows longer fishing campaigns and farther trips, hence, giving access to shoals not accessible with little boats.

[3] Actually, many experimental studies dealing with an *N*-person time independent prisoner's dilemma, consider the allocation of an endowment between two different investments, a private investment and a group investment. The private investment does not suffer from externalities; the returns are independent of the group's decisions. The group investment has the same status as a CPR within that framework. Some references are: Walker, J. and Gardner (1992), Ostrom, E., Gardner, et al. (1994), Apestiguia, J. (2001) and Cardenas, J. C., J. Stranlund, et al. (2002).

in a slightly different way to the one made by Herr, Gardner et al. (1997). The former are the external effects that occur only in the current period (within-period externality), while the later occur in the future periods (across-period externality).

Experimental research has shown that human subjects do not have a good perception of the future consequences of their current actions (Herr, Gardner et al. 1997; Moxnes 1998; Mason and Phillips 1997). One can therefore expect that in situations involving dynamic externalities, the outcome of individual decisions will be very inefficient. Static externalities in this kind of dynamic environment may enhance the perception of common property of the resource, leading to a more efficient exploitation. In order to evaluate this hypothesis, we compare the efficiency of the CPRs exploitation under two treatments (*A* and *B*). In treatment *A*, the exploitation of the CPRs only generates across-period externalities, while in treatment *B*, it generates both within-period externalities and across-period externalities.

The experiment is designed to test the predictions of a dynamic game of resource exploitation, with the presence of substitutes CPRs. We consider three kinds of behavior, and discuss the corresponding symmetric solutions: the sub-game perfect equilibrium outcome, the myopic outcome, and the joint profit maximization outcome. 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 others players optimal extraction plan. Under the assumption of myopic behavior, the optimization horizon is restricted to one period. The appropriator calculates the profit maximizing extraction for each resource, and then chooses the most profitable resource respecting the budget constraint. The joint profit maximization behavior corresponds to the outcome that would result if all appropriators cooperate in order to maximize the welfare (defined as the sum of all appropriator's profits for the whole optimization horizon).

Using survival data analysis, we evaluate the determinants of the resource choice path under these two treatments by estimating a conditional-competing risk set Cox proportional hazard model (Prentice, Williams et al. 1981). This approach is close related to the Quantal Response Equilibrium (QRE) analysis for extensive form games (Mckelvey and Palfrey 1998). However, a QRE can not be fit to explain the out-equilibrium behavior in our theoretical model because of the restrictions imposed by the dynamic nature of it. The main difference resides on the fact that our approach can not be interpreted as a concept of equilibrium of a game.

The paper is organized as follows. In *Section 2* we introduce the notations and the dynamic game model of substitute CPRs, and discuss the three benchmark predictions: sub-game perfection, myopia and joint profit maximization. *Section 3* presents the experimental design and the decision setting, and details the implementation in the laboratory. In *Section 4* we summarize our experimental findings and explain in detail de econometric model applied to data. *Section 5* concludes.

2. A Dynamic Game of Substitute Common Pool Resources' Exploitation

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

Although many interpretations are possible, we present the model in terms of substitute water resources. Let us suppose that *N* identical appropriators, indexed by *i*, extract water from one of the three available water resources in each period. Resource *1* is an unlimited private resource that could be bought in the market at a constant unit price. Resources *2* and *3* are CPRs, characterized at each period *t*, by a stock of available units[4]. Appropriator *i* extracts a quantity $y_{i,j}^t$ from the *j*-th resource (*j* = *1*, *2*, *3*) in period *t*. The evolution of the groundwater stocks are described by equation (1):

$$S_j^{t+1} = S_j^t - Y_j^t + r_j \qquad j = 2, 3 \tag{1}$$

$$S_2^0 < S_3^0 \text{ and } r_3 < r_2$$

where, S_j^t is the stock of available units of the *j*-th (= *2*, *3*) groundwater resource in period *t*,

r_j is the natural per period recharge of the *j*-th (= *2*, *3*) groundwater resource stock[5],

$Y_j^t = \sum_{\forall i} y_{i,j}^t$ is the total extraction from the *j*-th (= *2*, *3*) groundwater resource in period *t*.

Let us assume that each appropriator extracts water from only one resource in a given period. However, appropriators may eventually switch from one resource to another any time.

According to Equation (1), groundwater stocks grow naturally[6] with the recharge and decrease with extractions.

Extracted water generates a gross return to appropriator *i* in period *t*, given by:

$$u_i\left(y_{i,j}^t\right) = a \cdot y_{i,j}^t - b \cdot \left(y_{i,j}^t\right)^2 \qquad j = 1, 2, 3. \tag{2}$$

where $a, b > 0$.

Furthermore, we assume that the average (and marginal) cost of the extracted water from resource *1*, noted p_1, is constant. The average water extraction cost from resource *2* and *3* depends linearly on the available stocks and the total extraction of the period:

$$AC(S_j^t, Y_j^t) = p_j + z \cdot Y_j^t - f \cdot S_j^t \qquad j = 2, 3. \tag{3}$$

where $0 < p_3 < p_2$, $z, f \geq 0$; *z* measures the within period externality, and *f* measures the across period externality[7].

As a consequence of the hypothesis on the evolution of the available stocks (1) and the constant term in the average costs (3), resource *3* is more attractive than resource *2* at the time zero. On the other hand, resource *3* requires a larger sunk cost to be exploited, and cannot be accessed with the budget available at period zero.

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[4] These resources could be thoughts as shallow and deep groundwater.

[5] Note that the recharge is assumed to be constant here.

[6] If there were no extractions, groundwater stocks would growth indefinitely. So, a more complete specification of groundwater stocks evolution would demand the definition of a natural out-flow.

[7] In many empirical situations only across-period externalities are present. For example, there is no reason to think that pumping on the same basin by two individuals remotely located, will mutually affect each other net return within a period (Brozovic 2002).

Access to resource *1* is free. Access to resources *2* and *3* requires a constant and once-for-all sunk investment, c_j (*j = 2, 3*). Since borrowing is not possible, investors can rely only on their private wealth to access the resources[8].

The period *t* profit function of each appropriator depends on the choice of the resource:

$$U_i\left(y_{i,j}^t\right) = u_i\left(y_{i,j}^t\right) - AC_j^t \cdot y_{i,j}^t - I_j^t \cdot c_j \tag{4}$$

where I_j (*j = 2, 3*) is a binary variable, equal to 1 the first time the appropriator decides to extract from the *j*-th resource (*j = 2, 3*), and zero otherwise. We assume that appropriator i's objective function is to maximize the sum of their profits, $\sum_{s=1}^{T} U_i^s$. 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 the initial wealth.

In the absence of financial markets, appropriators must satisfy their budget constraint for financing the investments. Let us impose that $c_2 < W^0 < c_3$ [9], so the access to resource *2* is affordable in period 1, but access to resource *3* is only possible if enough profit is accumulated.

In each period, the appropriators must decide which resource to use and the amount to extract. Depending on the behavioral assumptions, we derive different benchmark solutions for the extraction game. We consider three kinds of behavior, which correspond to three symmetric solutions of the game: the sub-game perfect equilibrium outcome, the myopic outcome, and the joint profit maximization outcome. Let us call these benchmark solutions the Rational, Myopic and Optimum outcome, respectively.

Independently of the behavioral assumption, the solution of the extensive form game implies the search of a sub-game perfect equilibrium. The decision process consists in two steps: (*i*) the choice of the resource, and (*ii*) the choice of the amount to be extracted from it. Hence, appropriators proceed backwards. First, they calculate the return maximizing amount of extraction for each resource, and second, they choose the resource which generates the largest profit (proceeding backwards again).

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[8] In the literature the investment decision is treated as a strategic variable that enables an appropriator to accommodate or deter entry (Barham, Chavas et al. 1998). If entry is accommodated, the exploitation is less efficient than it would be in the case of deterrence (Aggarwal and Narayan 2004). The exploitation of the CPR must ensure the profitability of the initial investment. So, in order to evade excessive future pumping costs and quickly recuperate the investment charge, entry accommodation enhances current exploitation (the so-called "race for the water"). Conversely, the appropriator is able to fully enjoy the profits of a patient exploitation when the entry is deterred.

[9] In that case, resource *2* would be the shallow groundwater resource, while resource *3* would be a deep groundwater resource. The hypothesis on the evolution of stocks (1), are also interpretable in this way, reflecting many empirical situations [Barrocu, G. (2003), Dörfliger, N. (2003), Günay, G. (2003)].

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 others players optimal extraction plan. When deciding about the amount of extractions in each resource, they must know exactly in which periods they will use that resource. These periods may not be consecutives, because appropriators could change of resource meantime. The periods when appropriators switch from one resource to another, are called *transition periods*. In this way, the rational appropriators calculate, for each groundwater resource, an extraction path (taking the transition periods as given) that may consider non consecutive extraction periods[10]. The extraction path just described (taking the transition periods as given), is called feedback strategy if it is a function of the available stock in each t. Such a solution needs a particular information structure (Basar and Olsder 1999). More precisely, appropriators must perfectly observe the available stock of each resource at the beginning of each period. This allows adapting extractions to every period's conditions[11]. Conversely, if appropriators do not observe in every period the available stock, but just the initial one at the beginning of the game, they will not be able to adapt their extraction behavior. In that case, rational appropriators implement an open-loop strategy (Basar and Olsder 1999)[12].

Under the assumption of myopic behavior, the optimization horizon is restricted to one period. The appropriator calculates the profit maximizing extraction for each resource, and then chooses the most profitable available option under the budget constraint. Myopic behavior results in higher extraction than the rational behaving appropriators in the early periods of the game, while in the last period's extractions are lower. This difference is due to the capacity of rational appropriators to consider in their actual decision the future period's natural recharge of the available stocks. The bigger the natural recharge the greater the difference between rational and myopic extractions trajectories.

The optimum outcome consists to the decision that maximizes the sum of all appropriators' profit for the whole temporal horizon. This corresponds to the outcome that would result if all appropriators cooperate and maximize the joint profit. This cooperative behavior results in extraction trajectories with slightly positive slope, which would vanish if the natural recharge is null.

3. Experimental Design

The experimental protocol was designed to capture the fundamental aspects of the game described by equations (1)-(5). Though, in order to reduce the complexity of the decision environment some simplifications have been introduced. In each period, a subject decides from which one of the three available "accounts" he/she will extract his/her desired amount of "units". Given the parameterization (see *Table 1*), a subject earns experimental points depending on his/her unit order and on the available units in the chosen account during that period. No distinction was made between benefits and cost to facilitate subject's decision making.

[10] Rational appropriators are supposed to be able to go backwards on every branch of the decision tree, and find the one that maximizes their returns.
[11] So, it is said that 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 this strategies applied to modeling the fisheries exploitation).
[12] Hence, they commit to a fixed extraction path.

We analyze subjects' decisions under two treatments. In treatment *A*, only dynamic externalities (across-period externalities) affect accounts *2* and *3* (z=0). In treatment *B*, both static and dynamic externalities are considered (within and across-period externalities) (z=0.001). The values of parameters were calculated to assure that predictions and efficiency of the Myopic and Rational strategies remains the same under both treatments.

Table 2 shows the trajectory of the individual unit orders[13] for each benchmark strategy. All benchmarks begin ordering from account *2*. In the rational case, unit orders are made from account *2*, from the beginning of the game. While the same pattern is observed for the myopic benchmark, unit orders of the rational behaving subjects are higher at the beginning period. This similarity is due to the capacity of rational behaving subjects to incorporate the future naturally recharged units of accounts *2* and *3*, enhancing the "water race" (Provencher *et al*., 1993). Also, the "natural recharge" enables the myopic behaving subjects to order more in future periods by preventing the available units from diminishing too fast[14]. By the 4-th period, as in the rational strategy case orders switch to account *3*, in the myopic strategy case, before ordering from account *3* in period 5, orders are made from account *1*. Myopic subjects order from account *3* until the last period when they go back to order from account *1*. In the 8-th period, rational behaving subjects will choose the account *2*, to finish ordering from account *1* in the last period. Conversely, the optimum strategy unit orders from accounts *2* and *3* increase slightly over time. Lower unit orders from account *2* in the initials periods allow accumulating enough wealth to access account *3* and to rest in it, without ordering from account *1*.

Table 1: Parameterization

	Parameters	
	Treatment A	**Treatment B**
Group size (*N*)	5	
Benefit function	$a = 5.3$ $b = 0.09$	$a = 5.3$ $b = 0.087$
Cost function	$p_1 = 3.88$ $p_2 = 7.55$ $p_3 = 7.4$ $f = 0.01$	$p_1 = 3.9$ $p_2 = 7.55$ $p_3 = 7.4$ $f = 0.01$
Account evolution	$S_2^0 = 500$ $r_2 = 5$ $S_3^0 = 750$ $r_3 = 2$	
Access fee	$c_2 = 15$ $c_3 = 40$	
Available range of unit orders	$[0,50]$	

[13] Subjects can only order units from one account per period. The "–" means zero unit order.
[14] The greater is the "natural recharge" the farther the rational and myopic order predictions will be.

Experimental Implementation

All experimental sessions were conducted at University of Montpellier I utilizing the Z-Tree (Fischbacher 1998) computer system. Subjects were recruited from the pool of undergraduate students of LEEM[15], mostly majoring in economics or management[16]. No subject has ever participated in a similar experience. Recruitment was principally done by e-mail. Subjects were invited to participate in an experimental game lasting approximately 1.5h, and were told that they will receive a payment based on his/her decisions and the decisions of the group (in addition to a show-up fee).

At least two player groups 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 also were read aloud by an assistant. Understanding was checked individually by a questionnaire[17]. No practice rounds were performed.

Table 2: Trajectories

Period	Rational			Myopic			Optimum					
	Treatment A and B			Treatment A and B			Treatment A			Treatment B		
	Accounts			Accounts			Accounts			Accounts		
	1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
1	-	13	-	-	15	-	-	10	-	-	9	-
2	-	11	-	-	11	-	-	10	-	-	10	-
3	-	9	-	-	9	-	-	10	-	-	10	-
4	-	-	26	8	-	-	-	-	11	-	-	10
5	-	-	21	-	-	30	-	-	11	-	-	11
6	-	-	16	-	-	22	-	-	11	-	-	11
7	-	-	13	-	-	16	-	-	12	-	-	12
8	-	-	10	-	-	12	-	-	12	-	-	12
9	-	8	-	-	-	9	-	-	12	-	-	12
10	8	-	-	8	-	-	-	-	13	-	-	13
Efficiency	83.5 %			78.0 %			100 %			100 %		

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.

[15] Laboratory of Experimental Economics of Montpellier.
[16] In the treatment B session, some students of sciences were recruited.
[17] During the questionnary filling subjects were allowed to ask questions individually to the assistants.

Decision Setting

In each period, subjects choose independently and simultaneously the account from which to order units. Individual unit orders were restricted to values in the range $[0,50]$. All subjects made decisions simultaneously. Subjects were provided with three tables, one for each account, showing the return for each pair of available unit level and unit order in the allowable range[18]. Since we could not provide a complete table for all possible values of S_j, subjects were given a partial table as well as the formulae that was used to calculate the profit. Profits were expressed in "experimental points", and subjects knew the conversion rate that 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 accounts *2* and *3*. After each decision period subjects were informed about their own profits for that period. A "summary table" of the series was available, where information about previous periods accumulated wealth, net return, unit order (and from which account), and the available units in accounts *2* and *3*, could be checked. Corresponding

4. Experimental Results

We ran four sessions, that involved the participation of 55 subjects. Data of a total of 44 series (at the group level) was collected.

The benchmark strategies predictions shown in *Table 2* rely on the assumption that every subject behaves as predicted, hence we call them "unconditional benchmarks". Deviation from benchmark outcomes can occur for many reasons. 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. Furthermore, the individual budget constraint and the account choice trajectory make subjects heterogeneous. Therefore, an individual conditional benchmark should be calculated for each subject. In this paper, only comparisons of data to the unconditional benchmarks are performed.

We first analyze the fitting of individual data to the unconditional benchmarks. Then, the account choice is studied more deeply using an econometric model of survival data analysis.

Individual Unit Orders Analysis

In order to compare individual unit order data to benchmarks we use the Normalized Mean Square Deviation (NMSD) of individual unit orders. The larger the deviations of the data with respect to benchmarks, the larger the NMSD. The NMSD is calculated using formula (6):

$$\sum_{j=1}^{3}\sum_{t}\sum_{i}\left(y_{i,j}^{t}-y_{i,j}^{t\,e}\right)^2 \Big/ N\cdot\left(1+y_{i,j}^{t\,e}\right), \qquad (6)$$

[18] The information on the account 2 and 3 Tables corresponds to the net and the brut return, for the treatment A and treatment B cases, respectively. In the later case, subjects must deduce from the net mean return a percentage of the total unit orders on the account in the corresponding period.

where $y_{i,j}^{t\ e}$ is the predicted unit order from account *j* at period *t*.

Tables 3 and *4* depict NMSD measure by group for each series of treatments *A* and *B*, respectively[19].

OBSERVATION 1: For treatment *A*, the comparisons of the individual unit order data to the unconditional benchmarks designate the Optimum strategy as the best fitting one.

As it can be observed in the last row of *Table 3*, the Optimum strategy unconditional benchmark minimize de NMSD followed by the rational, and in the last place, the myopic benchmark. The differences in the NMSD measure are all significant[20]at the aggregate level[21]. If we look at the series level, the optimum strategy remains the best fitting one. Conversely, we can not distinguish between the rational and the myopic ones at least for the first two series.

OBSERVATION 2: For treatment *B*, the comparisons of the individual unit order data to the unconditional benchmarks designate the Optimum strategy as the best fitting one.

As in the case of treatment *A*, the optimum strategy unconditional benchmark minimizes de NMSD followed by the rational, and in the last place, the myopic benchmark (Table 4); and the differences in the NMSD measure are also significant at the aggregate level. At the series level, the difference in NMSD value for the myopic benchmark is significantly greater than the rational and optimum ones. However, the difference in NMSD measure between the optimum and the rational benchmark are not significant, excepting the second series. Thus, we can not distinguish which one of these two strategies better explains the data.

[19] In T*ables 3* and *4,* the **bold** font numbers indicate the strategy with the lowest deviation measure for each group.
[20] Confidence intervals have been constructed using the bootstrap non-parametric method (Efron B. 1995).
[21] If the confidence intervals limits do not overlap, we consider that the NMSD measure are significantly different.

Table 3: Normalized Mean Square Deviation. treatment A.

Treatment A				
Strategy		Rational	Myopic	Optimum
		Account	Account	Account
Series	Group	Total	Total	Total
1	1	352	534	**257**
	2	318	787	**231**
	3	1202	969	**647**
	4	1105	1086	**827**
	5	567	648	**458**
Mean [95% intervals]		708.8 [545.06 884.59]	804.8 [608.87 1036.5]	484 [367.99 631.89]
2	1	298	**102**	271
	2	392	865	**230**
	3	482	304	**298**
	4	572	412	**388**
	5	1204	1202	**715**
Mean [95% intervals]		589.6 [445.32 679.25]	577 [412.25 736.5]	380.4 [266.31 502.77]
3	1	208	**101**	271
	2	386	836	**264**
	3	**220**	940	255
	4	421	598	**243**
	5	630	447	**431**
Mean [95% intervals]		373 [305.06 449.97]	584.4 [425.66 742.42]	292.8 [216.55 369.93]
4	1	294	**121**	264
	2	278	957	**250**
	3	253	530	**231**
	4	421	464	**331**
	5	**274**	824	344
Mean [95% intervals]		304 [248.28 369.94]	579.2 [425.85 732.98]	284 [221.51 360.99]
Global Mean [95% intervals]		**493.85** [431.84 545.58]	**636.35** [551.29 726.42]	**360.3** [312.44 415.71]

Table 4: Normalized Mean Square Deviation. Treatment *B*.

Treatment A				
Strategy		Rational	Myopic	Optimum
		Account	Account	Account
Series	Group	Total	Total	Total
1	6	554	816	**378**
	7	1074	**835**	1019
	8	780	889	**513**
	9	1054	991	**698**
	10	786	578	**553**
	11	695	779	**565**
Mean [95% intervals]		823.95 [746.64 959.19]	814.6 [637.87 999.62]	621.21 [453.12 827.18]
2	6	437	1044	**284**
	7	667	885	**460**
	8	515	1077	**404**
	9	516	779	**345**
	10	569	841	**413**
	11	724	951	**520**
Mean [95% intervals]		571.52 [517.91 680.57]	929.39 [727.5 1115.2]	404.28 [303.92 495.86]
3	6	625	728	**542**
	7	436	921	**390**
	8	557	824	**438**
	9	426	921	**325**
	10	561	808	**356**
	11	606	883	**424**
Mean [95% intervals]		535.16 [471.94 602.03]	847.79 [650.5 1041.6]	412.34 [305.84 529.57]
4	6	568	851	**432**
	7	478	139	**85**
	8	568	918	**460**
	9	409	872	**300**
	10	461	731	**277**
	11	655	663	**446**
Mean [95% intervals]		523.19 [376.31 500.16]	695.58 [517.94 868.55]	333.18 [233.52 424.54]
Global Mean [95% intervals]		**613.46** [567.11 644.34]	**821.84** [729.94 917.23]	**442.75** [380.85 503.34]

OBSERVATION 3: The rational and myopic benchmarks fit better the data in treatment *A* than in treatment *B*.

The comparison of the mean NMSD measures for both treatments does not show any difference for the optimum outcome. But for the rational and myopic predictions, we find that the NMSDs for treatment *B* are significantly larger than for treatment *A*. This may be evidence for a lower capacity of the socially optimum outcome to come out when exploitation of the CPRs only produces dynamic externalities. Moreover, as shown in Figure 1 order paths in treatment *A* lie above the order paths of treatment *B* ones. Particularly, the account *2* initial orders in treatment A are significantly greater than in treatment *B* while, during the last periods the opposite occurs (between periods 3 and 6 no significant differences are observed). In both treatments, account *3* order paths are similar at the initial period (period 4). Anyway, treatment *A* show higher orders and a more markedly decreasing trend with respect to treatment *B* for which, no orders from account *3* were observed in the last period (period 10). Orders from account *1* are quite similar in both treatments. These significant differences allow us to conclude that the presence of both, dynamic and static externalities in the exploitation of the CPRs, enhance the emergence of a socially optimum behavior.

As can be seen in Figure 1, orders from account *2* and *3* are significantly below the predicted levels for both treatments. A possible explanation to this may be the positive orders from account *1* observed all along the decision time, strongly contrasting with the benchmark predictions.

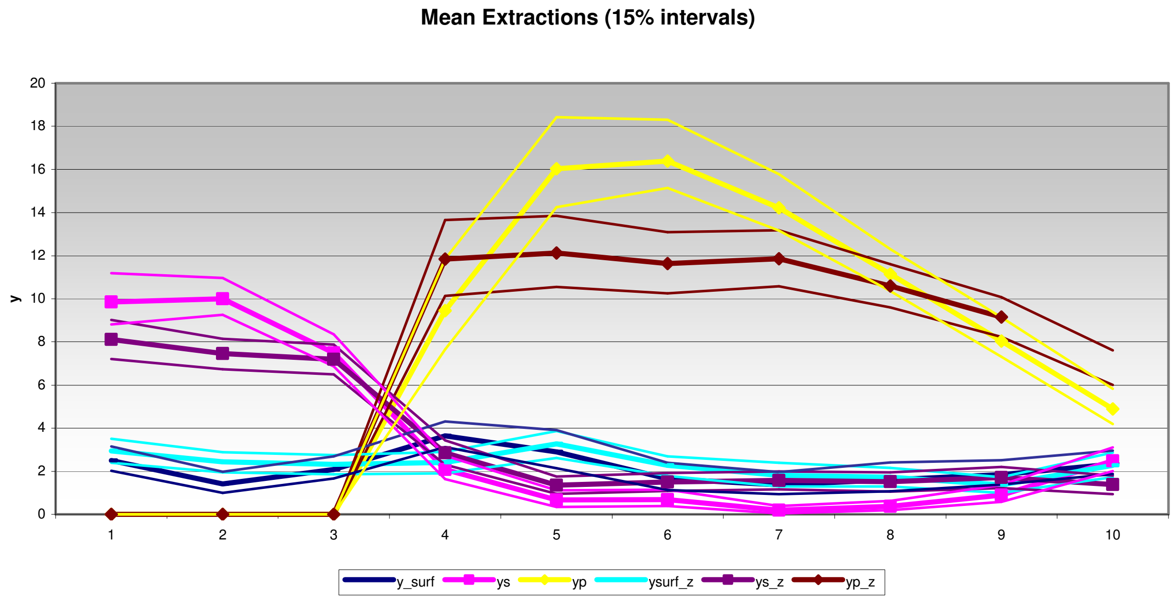


Figure 1: Treatment *A* and *B* Mean Orders.

OBSERVATION 4: Observed account choices differ from the unconditional benchmarks in both treatments.

Data can differ from benchmarks in two aspects, (*i*) unit order, and (*ii*) the account choice. Obviously, the second deviation implies the first one. If the account choice differs from the predicted one, two "errors" will appear. Firstly, unit orders would be positive in the chosen account while they were supposed to be zero, and secondly, they will be zero in the account where they were not supposed to be zero. The normalized measure minimizes the double counting of the account choice deviations, because it places a very high weight on the first type of error and a near zero weight on the second one[22]. The high values of NMSD measures indicate that the deviations are mainly explained by "wrong" account choices. The significantly positive orders from account *1* and *2* in every period support this assert (see Figure 1).

In the next subsection, we analyze the account choice decision. In order to asses an eventual treatment effect, and to better understand the pattern of observed account choices, we formulate a survival data econometric model of competing risks with ordered events (Lancaster 1990). This kind of econometric model allows us to estimate the impact of the presence of both, dynamic and static externalities, on the probability of choosing an account in each period.

Account Choice Analysis

In every period, appropriators have the choice between different resources (i.e. accounts), where the choice set depends on their actual wealth and their past decisions. According to the theoretical behavioral assumption, appropriators look forward to maximize their profits, and therefore choose individually (socially) the account that enables them to obtain the maximum individual (social) return. But appropriators can make errors in doing this choice; they may have "trembles" or, misperceptions about the future return of each account (Selten 1975; Mckelvey and Palfrey 1998). Quantal response equilibrium theory (QRE) assumes that errors involving small individual losses are more likely than errors generating large individual losses. The specification of a one-parameter error distribution, allows QRE theory to predict which of the out-of-equilibrium branches of the decision tree is an QRE.

As has been shown in the previous sub-section, the bad fit of our experimental data to the unconditional benchmarks is largely explained by the "wrong" account choices. However, a QRE can not be fit to explain this out-equilibrium behavior because of the restrictions imposed by the dynamic nature of the theoretical model. In each period, the only available information to appropriators is the remaining stock in resources *2* and *3*, and their own decision history (perfect recall). The available stock depends on past extractions of all appropriators and determines the expected future return of each resource (only resource *2* and *3*). Thus, each player errors in each information set are not independent. Even if one assumes that independency is not problematic, a computational problem remains because the calculation of resource *2* and *3* expected return requires the computation of higher order integrals. As a consequence, we implement a different approach to study the account choice decision.

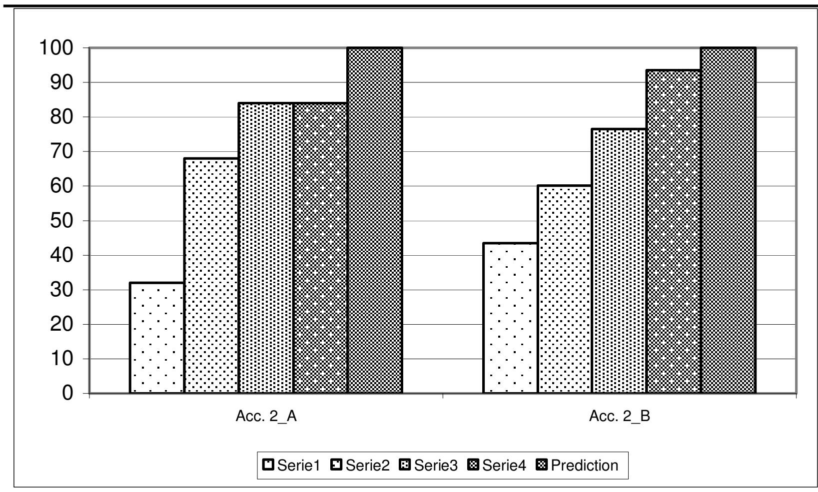
In order to detect an eventual treatment effect and to better understand the pattern of observed account choices, we formulate a survival data econometric model of competing risks with ordered events (Lancaster 1990). Let us consider the different accounts as the elements of a set of states. A transition is the movement of an individual from one state to another. Transition data records the sequence of states that were occupied and the times at which

[22] The NMSD measure is similar to the Mean Square Deviation (MSD) used in Herr, A., R. Gardner, et al. (1997). It suffices to replace $y_{i,j}^{t\ e}$ by zero in the NMSD to obtain the MSD measure.

movements between them occurred[23]. In each period, appropriators must decide from which resource to extract conditional to the wealth accumulated up to that period and the resource exploited in the previous periods. The account choice in the first period of the game determines the initial state from which transitions will occur. Then, we study separately the first period account choices and the account changes produced in later periods.

First period account choice

In the first period subjects can choose only between accounts *1* and *2* (account *3* is out of their budget constraint). *Figure 1* shows the percentage of subjects choosing account *2* in each series in the first period. We can observe that the percentage of subjects choosing account *2* tends to the unconditional prediction[24] with the repetition of the series. It grows steadily from 32% up to 84% in the third and fourth series for treatment *A*. In treatment *B*, the percentage also grows from 43% up to 94% in the fourth series. The Pearson chi-squared statistic indicates independency of the treatment variable and the account choice for all series.



Pearson's Chi-squared statistic	0,6771 (0,411)	0,127 (0,722)	0,1039 (0,747)	0,135 (0,711)

Figure 1: First period account choice

Transitions

At the beginning of each period subjects have the choice between either keeping the previous period account or switching to another account. Allowing appropriators to make errors in choosing their account implies that in every period, each account has a positive probability of being chosen. However, this probability of choice depends on the decision history. In which information set the appropriators will be in each period depends on their past decisions which in turn, determine the accumulated wealth and expected profit of each account. Thus, the

[23] It is closely related to duration econometric models. The main difference resides on the number of destination states. While in duration models there are only two possible states, models of transition data deal with multiple states.
[24] As we can see in Table 2, all unconditional benchmarks predict to begin ordering from account *2*.

probability of an account to be chosen in each period is not independent of the choices made in the past. For example, if appropriator *i* has never chosen account *2* but he/she has always ordered from account *1*, the probability of this event to occur may grow (or decrease) with the passage of time. One way to formalize this situation is to formulate a survival data model called "competing-risk set model". This statistical model postulates the existence of *K* independent random variables, $T_1,...,T_K$, one for each event, which are generally called latent durations or latent survival times, and then suppose that the tangible occurred event is determined by whichever of the $\{T_k\}$ is the least, and that this minimum is the duration we actually observe[25]. At the end of the analysis time, the random variables that were not observed are called "censored durations". Two important related functions for transition and duration models are the *survivor function* and the *hazard function*. The survivor function is just the complement of the probability distribution of a duration variable[26]. Hence, it gives the probability for a duration *T* to be strictly greater than *t*. The rough interpretation of the hazard function is that it gives the probability of exit from a state in a short interval of time after *t*, conditional on the state still being occupied at *t* (Lancaster 1990).

This "competing-risk set model" does not totally correspond to our theoretical benchmark. To illustrate that, let us continue with the previous example. In that situation the event "switch to account *2* for a second time in *t*, given order from account *1* in *t-1*" has probability zero. The intuition is straightforward. This event is not at risk; for being at risk, appropriator *i* would have had ordered from account *2* once, and changed to another account after that. In that case, he/she would have the possibility to switch to account *2* a second time. Then, the *K* random variables are no longer independent, but they are ordered and each event exposition to risk is conditional on the account exploited in the previous periods. *Table 7* enumerates all the possible events (or states) given the parameterization of the experiment presented in *Table 1*.

Table 7: Transition types

Event Type	Description
-	-
2	Order from acc. 1 in t given order from acc. 2 in t-1, first time
3	Order from acc. 1 in t given order from acc. 2 in t-1, second time
4	Order from acc. 1 in t given order from acc. 2 in t-1, third time
5	Order from acc. 1 in t given order from acc. 2 in t-1, fourth time
6	Order from acc. 1 in t given order from acc. 2 in t-1, fifth time
7	Order from acc. 1 in t given order from acc. 3 in t-1, first time
8	Order from acc. 1 in t given order from acc. 3 in t-1, second time
-	-
10	Order from acc. 2 in t given order from acc. 1 in t-1, first time
11	Order from acc. 2 in t given order from acc. 1 in t-1, second time
12	Order from acc. 2 in t given order from acc. 1 in t-1, third time
13	Order from acc. 2 in t given order from acc. 1 in t-1, fourth time
14	Order from acc. 2 in t given order from acc. 1 in t-1, fifth time
15	Order from acc. 2 in t given order from acc. 3 in t-1, first time
16	Order from acc. 2 in t given order from acc. 3 in t-1, second time
17	Order from acc. 3 in t given order from acc. 1 in t-1, first time
18	Order from acc. 3 in t given order from acc. 1 in t-1, second time
19	Order from acc. 3 in t given order from acc. 2 in t-1, first time
20	Order from acc. 3 in t given order from acc. 2 in t-1, second time

[25] See Chapter 19 in Mátyás, L. and P. Sevestre, Eds. (1996). The Econometrics of Panel Data. A Handbook of the Theory with Applications. Advanced Studies in Theorical and Applied Econometrics. Dordrecht, Kluwer Academic Publishers.

[26] It owns his name to applications in medicine and biostatistics where duration usually refers to the lifetime of an organism.

Following the method proposed by (Prentice, Williams et al. 1981), known as the conditional risk set model, we formulate a conditional-competing risk Cox proportional hazard model, which incorporates the possibility that two competing events coexist. For example, an individual who orders from account *2* and who never paid the access fee to account *3*, has a choice in the next period between moving to account *1* or account *3*, or stay with account *2* (two competing events) if his/her budget constraint allows him/her. The case where account *3* is not feasible (only one alternative), corresponds to the pure conditional risk set model.

The Cox proportional hazard hypothesis consists to write the hazard function at period *t* given the covariate and counting processes at period *t*, as a product of an arbitrary function of time, the baseline hazard function, and an exponential function of the covariates[27]. We estimate using the statistical package Stata, a stratified model that considers the time from the beginning of the study as the time scale of the baseline hazard (Equation 7).

$$\lambda(t) = \lambda_{0s}(t)\exp\{z(t)\beta_s\} \qquad (7)$$

A double stratification has been done for the estimation, event type (*Table 7*) and wealth[28] are the stratification variables. The covariates coefficients β are commonly estimated to all stratums, but each stratum has a different baseline hazard. Maximum likelihood estimation of the covariate vectors of equation 7 relative hazard factor is performed. In order to search for treatment and experience effects, and to identify the variables that impact decision, we consider time-invariant and time-variant covariates. As time-invariant covariates we include a dummy variable that takes value 1 for treatment *B* (*inter*) and the lagged-profit (*lag_profit*)[29,30]. The time-variant covariates are the one-lagged wealth level (*intlag_W*) and the ratio of the available units in accounts *2* and *3* at the beginning of the transition period (*rapstock*). The two time-variant covariates show a non linear relation with time. Thus, we consider four additional covariates (*intlag_W_time*, *intlag_W_time*^2, *rapstock_time* and *rapstock_time*^2).

Table 8 summarizes the estimated coefficients and the specification test performed (proportional hazard assumption test). The next observations resume our findings.

OBSERVATION 5: The relative abundance of available units in account *2* encourage switching between accounts.

The coefficient of the ratio between the available units in accounts *2* and *3* is highly significant. This indicates that the probability of leaving an account for another one is multiplied by 4.3 when the ratio of available units in account *2* and *3* is incremented by one point (holding the other covariates constant). As a consequence of the non-linear relation of *rapstock* with time (convex function of time), the impact of the relative abundance of units in account *2* depends on the period considered. For example, in period 1 a one point increment of *rapstock* (*ceteris paribus*) increases the hazard by 436%, while in period 10 it reduces it by 11%. Thus, it is more probable that switching between accounts occurs at the beginning and

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[27] This model is due to Cox (1972) and can be found in every textbook of survival data econometrics see Lancaster 1990.
[28] We have constructed wealth intervals (50 points each).
[29] As first glance we may think that the lagged-profit varies continuously with the time. We fitted fractional polynomials to graphically evaluate this relation, which results to be negligible.
[30] Three other dummy variables for the first three series (*serie1*, *serie2* and *serie3*) were considered. But, they were excluded of the final model because they were highly insignificant.

the end of the dynamic game. This observation contrasts with the benchmark predictions; the switching is attended for the middle of the optimization horizon (periods 4 and/or 5 depending on the benchmark strategy).

OBSERVATION 6: High one-lagged profit discourages switching between accounts.

The impact of the accumulated wealth up to the beginning of the transition period can be divided into two effects: (i) the one-lagged profit, and (ii) the one-lagged wealth. The later has not a significant impact. The profit earned in the period preceeding transition has little impact; it reduces the risk of an account change by 2,8% when it is incremented in one point. This sign is in accordance with predictions, and supports the economic intuition of changing the account when it doesn't pay.

OBSERVATION 7: The presence of both, dynamic and static externalities reduces the risk of changing the account.

The presence of within-period externalities (in addition to the across-period externalities) in accounts *2* and *3*, reduces the hazard by 63%. Dummy variables introduced to determine an experience effect were excluded from estimation because they were all no significant.

5. Conclusion

The theoretical model considered in this paper, focuses attention on the choice between three imperfectly substitute resources (CPRs) in a dynamic framework. In dynamic environements, the exploitation of CPRs generate appropriation externalities that may spill over future periods. Then a distinction must be made between dynamic (time dependent) and static (time independent) externalities, and it is done in an a slightly different way to the one made by Herr, Gardner et al. (1997). The former are the external effects that occur only in the current period (within-period externality), while the later occur in the future periods (across-period externality).

One can expect that in situations involving dynamic externalities, the outcome of individual decisions will be very inefficient as a consequence of possible misperceptions of players about the future impacts of their current actions. Static externalities in this kind of dynamic environment may enhance the perception of common property of the resource, leading to a more efficient exploitation. In order to evaluate this hypothesis, we compare the efficiency of the CPRs exploitation under two treatments (*A* and *B*) with equal predictions. In treatment *A*, the exploitation of the CPRs only generates across-period externalities, while in treatment *B*, it generates both within-period externalities and across-period externalities.

We examine benchmark predictions for different behaviour assumptions in both treatments, namely, the joint payoff maximization outcome (optimum), the sub-game perfect equilibrium outcome (rational), and an outcome consistent with temporally myopic behaviour (myopic). Our findings show that behavior is not far from the optimum one in both treatments. It is not possible to distinguish which treatment is significantly closer of the optimum outcome. However, subgame-perfection and myopia fit better the treatment *A* data. This may be evidence for a lower capacity of the socially optimum outcome to come out when exploitation of the CPRs only produces dynamic externalities. Moreover, extractions from CPRs are significantly lower for many periods in treatment *B* than in treatment *A*, which is in accordance with a cooperative behavior. Additionally, the presence of static externalities reduces the switching between resources.

Table 8: Estimates coefficients

Variables	inter	lag_profit	rapstock	intlag_W	rapstock_time	rapstock_time^2	intlag_W_time	intlag_W_time^2
Coef. (Robust Std. Err.)	-0,6283936 (0,0690813)	-0,0282101 (0,0037692)	4,304288 (0,5053008)	0,0018821 (0,0022794)	-0,7365922 (0,1125204)	0,0307634 (0,0063289)	0,0004744 (0,0006123)	-0,0000888 (0,0000416)
Z	-9,1	-7,48	8,52	0.83	-6,55	4,86	0,77	-2,13
P>|z|	0,000	0,000	0,000	0,409	0,000	0,000	0,438	0,033
Wald Test	Chi2(8) = 767,09 Prob> Chi2 = 0,000							
Proportional Hazard Assumption Test								
rho	0,00352	-0,0154	-0,07906	0,03344	0,09128	-0,09225	0,01239	-0,02613
chi2	0,00	0,05	1,73	0,21	2,07	1,79	0,02	0,08
Pr > Chi2	0,9608	0,818	0,1879	0,6459	0,1504	0,1813	0,8855	0,7737
Global Test	Chi2(8) = 15,51 Prob> Chi2 = 0,05							

Appendix 1: Equilibrium Derivation

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

Myopic outcome

In the myopic behavior case, the optimization horizon is just one period. Supposing that everybody behaves myopically, the myopic appropriator calculates a subgame perfect equilibrium at each period. Hence, firstly the profit maximizing extraction for each resource, $y_{i,j}^{t^*}$ (*j = 1, 2, 3*), must be determined, and secondly, he/she chooses the most paying available resource, $j_i^{t^*}$, under the budget constraint. The for each $t = 1,...,T$

$$j_i^{t^*} = \sup\left\{U(y_{i,j}^{t^*}) \middle| j = 1,2,3\right\} \text{ u.c. } c_j \le W_i^t \qquad \text{A2.1}$$

where $y_{i,j}^{t^*} = \max\limits_{y_{i,1}^t} U_i\left(y_{i,j}^t\right) = \dfrac{p_j - f \cdot S_j^t}{2b + (n+1)z}$ $\qquad j = 2, 3 \qquad$ A2.2

and $y_{i,1}^{t^*} = \max\limits_{y_{i,1}^t} U_i\left(y_{i,1}^t\right) = \dfrac{p_1}{2b}$. $\qquad$ A2.3

Rational outcome

To decide about which resource to use, appropriators compare the flows of future net returns generated by the exploitation of each resource. The rational behaving appropriators internalize the impact of their current extractions on their own future returns. Then, they must know exactly in which periods they will use that resource. These periods may not be consecutives, because appropriators could change of resource meantime. The periods when appropriators change of resource, are called *transition periods*.

Let be,

$[1, T]$, the whole optimization horizon (finite)

$V_{i,j}^{t0,tf} = \sum_{\tau=t0}^{tf} U_{i,j}^{\tau*}$, the sum from period t_0 to t_f, of the individual *i*'s net return obtained by the optimal exploitation of the *j*-th resource, taking as the optimization horizon, for the resources *2* and *3* cases, the time interval from t_0 to t_f;

$U_{i,j}^{t^*}(t_0, t_f)$ where $t \in (t_0, t_f]$, the individual *i*'s net return in period *t*, obtained by the optimal exploitation of the *j*-th resource (*j = 2, 3*), taking as the optimization horizon the time interval from t_0 to t_f,

$U_{i,1}^{t^*}$, the individual *i*'s net return in period *t*, obtained by the optimal exploitation of the resource *1* (which are independent of time),

$\tilde{t}$, the first period for which the condition $U_{i,j}^{t_f *}(t_0, t_f) \leq U_{i,1}^{t_f *}$ is satisfied,

$\hat{t}$, the first period for which the condition $W_i^{\hat{t}} \geq c_3$ is satisfied (the budget constraint allows to invest in the access to resource *3*).

At each final node of the tree, the appropriator must calculate his/her optimal extraction path, taking the extraction path for the others appropriators as given.

First step:

Taking the optimization horizon $\lfloor t_0, t_f \rfloor$ as given, each appropriator calculates a feedback strategy for resources *2* and *3*, supposing that there are *n-1* other appropriators behaving in the same manner (Equation A2.4). Individual optimal extraction at each period $t \in \lfloor t_0, t_f \rfloor$ is given by the Equation A2.11.

$$y_j^t(S_j^t) = C_j^t \cdot \left[A_j^t \cdot E_j^t + (f \cdot r_j - d) \cdot (G_j^t + F_j^t)\right] \qquad \text{A2.4}$$

where,

$$A_j^t = a - p_j + f \cdot S_j^t, \qquad \text{A2.5}$$

$$G_j^t = (E_j^t - 1) - \rho \cdot f \cdot C_j^{t+1}(E_j^{t+1} + F_j^{t+1} - 1) \cdot \left[E_j^{t+1} \cdot C_j^{t+1} \cdot 2(b + zn) - 1\right] \qquad \text{A2.6}$$

$$E_j^t = 1 + \left(\frac{1}{C_j^t} - D\right)\frac{1}{f \cdot n}, \qquad \text{A2.7}$$

$$D = 2b + (n+1)z, \qquad \text{A2.8}$$

Second step:

The appropriator choose de transition periods taken the transition periods of her/his rivals as given, and supposing that everybody extraction behaviour is in accordance with the feedback strategy.

$$C_j^t = 1 \Bigg/ \left\{ D - fn \sum_{\tau=t+1}^{T} \rho^{\tau-t} \left[f \cdot E_j^{\tau} \cdot C_j^{\tau} \left[1 + \sum_{s=t+1}^{\tau-1} \prod_{q=s}^{\tau-1} \left(- fn \cdot E_j^{q} \cdot C_j^{q} \right) \right] f \cdot \left[2 \cdot \left(1 - fn \sum_{s=t+1}^{\tau-1} E_j^{s} \cdot C_j^{s} \cdot \left[1 + \sum_{e=t+1}^{\tau-2} \prod_{q=e}^{\tau-2} \left(- fn \cdot E_j^{q} \cdot C_j^{q} \right) \right] \right) \right. \right. \right.$$

A2.9

$$\left. \left. \left. - 2(b + zn) \cdot E_j^{\tau} \cdot C_j^{\tau} \left[1 + \sum_{s=t+1}^{\tau-1} \prod_{q=s}^{\tau-1} \left(- fn \cdot E_j^{q} \cdot C_j^{q} \right) \right] \right] \right] \right\}$$

$$F_j^t = \sum_{\tau=t+2}^{T} \rho^{\tau-t} \left\{ f \cdot E_j^{\tau} \cdot C_j^{\tau} \left[1 + \sum_{s=t+1}^{\tau-1} \prod_{q=s}^{\tau-1} \left(- fn \cdot E_j^{q} \cdot C_j^{q} \right) \right] \cdot \left[1 - 2(b + zn) \cdot \left[\left(E_j^{\tau} - 1 \right) C_j^{\tau} + \sum_{e=1}^{\tau-2} E_j^{\tau} \cdot C_j^{\tau} \left[1 + \sum_{s=e+1}^{\tau-1} \prod_{q=s}^{\tau-1} \left(- fn \cdot E_j^{q} \cdot C_j^{q} \right) \right] \cdot \left[1 + fn \cdot C_j^{s-1} \left(F_j^{s-1} + G_j^{s-1} \right) \right] \right] \right] + \right.$$

$$\left. + f \cdot \left(1 - fn \sum_{h=t+1}^{\tau-1} E_j^{h} \cdot C_j^{h} \cdot \left[1 + \sum_{k=t+1}^{h-1} \prod_{q=k}^{h-1} \left(- fn \cdot E_j^{q} \cdot C_j^{q} \right) \right] \right) \cdot \left[\left(E_j^{\tau} - 1 \right) C_j^{\tau} + \sum_{e=1}^{\tau-2} \left(E^{\tau} \cdot C^{\tau} \left[1 + \sum_{s=e+1}^{\tau-1} \prod_{q=s}^{\tau-1} \left(- fn \cdot E^{q} \cdot C^{q} \right) \right] \cdot \left[1 + fnC^{s-1} \left(F^{s-1} + G^{s-1} \right) \right] \right) \right] \right\} \qquad \text{A2.10}$$

The optimal extraction trajectory that results is given by:

$$y_j^{t*} = C_j^t \left\{ E_j^t \left(a - p_j \right) \cdot \left(1 - fn \cdot E_j^{t-1} \cdot C_j^{t-1} \cdot \left[1 + \sum_{s=1}^{t-2} \prod_{q=s}^{t-2} - fn \cdot E_j^{q} \cdot C_j^{q} \right] \right) + E_j^t S_j^0 f \cdot \left[1 - fn \cdot E_j^{t-1} \cdot C_j^{t-1} \cdot \left[1 + \sum_{s=1}^{t-2} \prod_{q=s}^{t-2} \left(- fn \cdot E_j^{q} \cdot C_j^{q} \right) \right] \right] + \right.$$

$$\left. + fr \cdot \left[E_j^t + G_j^t + F_j^t + \sum_{s=1}^{t-1} \left(E_j^s + G_j^s + F_j^s \right) \cdot \prod_{e=s}^{t-1} - E_j^{e+1} fnC_j^{e} \right] \right\} \qquad \text{A2.11}$$

Optimum Outcome

The optimum outcome consists to the decision that maximizes the sum of all appropriators' net returns for the whole temporal horizon. The procedure to find the transition periods is similar to that reported for the Rational outcome case. The unique difference is in the calculation of the extraction trajectories for resources *2* and *3*. So, the Equation A2.8 is replaced by:

$$D = 2b + 2nz \qquad \text{A2.12}$$

Also, Equation A2.9 is replaced by:

$$C_j^t = 1 \Big/ \Bigg\{ D - fn \sum_{\tau=t+1}^{T} \rho^{\tau-t} \Bigg[fn \cdot E_j^{\tau} \cdot C_j^{\tau} \Bigg[1 + \sum_{s=t+1}^{\tau-1} \prod_{q=s}^{\tau-1} \left(- fn \cdot E_j^{q} \cdot C_j^{q} \right) \Bigg] fn \cdot \Bigg[(1 - 2b - zn) \cdot \Bigg(1 - fn \sum_{s=t+1}^{\tau-1} E_j^{s} \cdot C_j^{s} \cdot \Bigg[1 + \sum_{e=t+1}^{\tau-2} \prod_{q=e}^{\tau-2} \left(- fn \cdot E_j^{q} \cdot C_j^{q} \right) \Bigg] \Bigg)$$

$$- 2(b + zn) \cdot E_j^{\tau} \cdot C_j^{\tau} \Bigg[1 + \sum_{s=t+1}^{\tau-1} \prod_{q=s}^{\tau-1} \left(- fn \cdot E_j^{q} \cdot C_j^{q} \right) \Bigg] \Bigg] \Bigg] \Bigg] \Bigg\} \qquad \text{A2.13}$$

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