The Beijer Institute
of Ecological Economics

DISCUSSION PAPER

Beijer Discussion Paper Series No. 232

Managing resources with potential regime shifts

Using experiments to explore social – ecological linkages in common resource systems

Therese Lindahl, Anne-Sophie Crépin and Caroline Schill. 2012.

The Beijer Institute of Ecological Economics
The Royal Swedish Academy of Sciences
Box 50005 SE-104 05 Stockholm Sweden
Phone: +46 8 673 95 00 Fax: +46 8 15 24 64
E-mail: beijer@beijer.kva.se

Managing resources with potential regime shifts: Using experiments to explore social – ecological linkages in common resource systems*

Therese Lindahl[1,ψ], Anne-Sophie Crépin[1,2] and Caroline Schill[1].

1. The Beijer Institute of Ecological Economics
The Royal Swedish Academy of Sciences
Box 50005, 104 05 Stockholm, Sweden
2. Stockholm Resilience Centre, Stockholm University,
10691 Stockholm Sweden

Abstract

We use laboratory experiments to analyze how appropriators in a common pool dilemma react to potential abrupt changes in the resource renewal rate. We let groups of 3-4 subjects harvest a renewable resource during an unknown number of periods. Whereas some of the groups face a resource with a logistic growth function, other groups share a resource that regenerates according to a logistic growth resource for relatively large stocks but if the resource stock falls below some critical value or threshold, regeneration drops dramatically. The optimal group strategy is the same for both treatments; to stay at the maximum sustainable yield for as many periods as possible. When there is no threshold in the resource dynamics, the usual tragedy of the commons emerges in about 50% of the cases. However, groups that face a resource dynamics with a threshold are more careful and more successful in their management. We argue that the threat of reaching the threshold triggers more efficient communication within the group which enables not only commitment for cooperation but also knowledge sharing about the resource dynamics, which together can explain why these groups perform better.

* We gratefully acknowledge financial support from the 7th framework European Union projects Arctic Tipping Points, (ATP, FP7-226248),and Arctic Climate Change Economy and Society, (ACCESS, FP7-265863), and from Ebba and Sven Schwartz foundation. We are grateful for experimental assistance from Nikolina Oreskovic and Johanna Drie and fruitful comments from participants at the final meeting of the ATP project, January 25th, 2012 in Tromsö Norway.
ψ Corresponding author: therese@beijer.kva.se; phone: + 46 8 673 97 09; fax: +46 8 15 24 64

1 Introduction

Common resources have usually been identified from their users' perspective; the user group can exclude others from using the resource but rivalry and non-excludability prevail within the group. These features often cause over-exploitation, a *tragedy of the commons* (Hardin, 1968), unless users find ways to cooperate. The prevalence of common resources and their often associated inefficiencies have given rise to an extensive literature aiming at identifying factors influencing management (see Ostrom et al (eds.), 2002 and Ostrom, 2006 for comprehensive overviews).

Most of these studies assume a fixed resource stock or relatively simple ecosystem dynamics. However, natural goods and services stem from ecosystems with complex dynamics involving temporal and spatial scale issues, multiple species interactions, and complex ecological feedback loops (See e.g. Levin, 1998). Ecosystem complexity implies that changes in ecosystems are not necessarily smooth. Some systems exhibit potential attracting alternate stable states involving positive feedback loops combined with changes in slow variables that trigger bifurcations (Scheffer, 2009). If some thresholds are trespassed, large, dramatic transformations can interrupt smooth changes in the system, creating so-called regime shifts (Scheffer et al, 1993; Van de Koppel et al, 1997; Nyström et al, 2000; Carpenter, 2003 and Scheffer et al, 2001). Regime shifts can lead to large, abrupt, and potentially persistent changes in the mix of produced ecosystem goods and services with significant impacts on human well-being (MA, 2005; Stern, 2006). A number of case studies document that regime shifts have occurred in many different ecosystems ranging from ocean circulation patterns to lakes and savannahs and the frequency of these phenomena seems to be increasing (Steffen et al, 2004; Lenton et al., 2008). The Arctic region for example, is a vital and vulnerable component of the Earth's environment and climate system, where climate change may trigger tipping points (Wassman and Lenton, 2012). Simultaneously, the Barents Sea - one of the most active fishing area in the world - is largely influenced by Arctic currents, sea-ice and icebergs. Marine mammals are very abundant in this region but the increasing human activities are threatening this population. The Barents Sea is certainly one place where we can foresee radical changes that will greatly affect fish stocks (ACIA, 2005).

Regime shifts pose significant challenges to natural resource management structures that mostly focus on smooth dynamics, with easily predictable and controllable changes (Holling and Meffe, 1996). Theoretical studies show that management can become relatively demanding as even marginal changes can cause radical, potentially irreversible, ecosystem transformations (Crépin, 2003; Wagener, 2003; Brock and Starrett, 2003; Ludwig et al, 1978; Anderies et al, 2002; Nævdal, 2001). Moreover, omitting important slow dynamics from the analysis can easily lead to management errors with substantial welfare consequences (Crépin, 2007) and policy instruments, like taxes, may not necessarily work (Weitzman, 1974 and Crépin et al, 2011). The impact that resource users' actions have on resource dynamics also matters (Polasky et al, 2011).

In a common resource management setting, a regime shift can magnify the externality associated with non-cooperation (Mäler et al, 2003 and Kossioris et al, 2008) or cause other kinds of suboptimal outcomes (over-exploitation or underutilization) depending on the initial state of the system (Crépin and Lindahl, 2009). Moreover, the outcomes of these common pool game theoretic settings depend very much on the underlying behavioral assumptions of the model: do users cooperate or not and how do users respond to changes in the resource stock? To improve our understanding of these social ecological systems and to be able to speak to the optimal set of policies it is thus crucial to explore the linkages between ecological characteristics and human behavior.

Collecting empirical data on human behavior under the influence of regime shifts is challenging and time consuming because it requires precise information about the situation before and after the shift, which is hard to get. However, even if such data is available, the chance is rather small that both ecological and socioeconomic data have been gathered in the same region and for the same period. (Biggs et al 2009; Walker and Meyers 2004)

Experiments are randomized evaluations that can measure the impact of specific drivers by randomly allocating individuals to treatment groups. Relative to traditional empirical economics, experiments provide an advantage by creating exogenous variation in the variables of interest, allowing us to establish causality rather than mere correlation. (List, 2006). The value of using experimental methods to gather empirical data on behavior in complex social-ecological systems has already been documented (see e.g. Janssen et al, 2010 and Cardenas et al, 2010). In a common resource game assuming temporal and spatial resource dynamics, Janssen (2010) finds that these aspects of resource dynamics have significant influence on the institutional rules on where and when to appropriate. Complexity can also be found within the social context. Many common resources, like irrigation systems, have inherent institutional asymmetries. Experiments on such irrigation games have shown the influence social norms have on appropriation strategies (Anderies et al, 2010).

However, to our knowledge, no one has ever tried to experimentally assess the effects of regime shifts on resource users' management of common resources, which is the purpose of this study. More specifically we will compare two experimental treatments. In both these treatments users face a common pool dilemma, but whereas some groups face a dilemma with simple resource dynamics, other groups face a more complex resource dynamic involving a potential regime shift. How will the existence of a potential regime shift influence individual strategies for cooperation and resource harvesting? Will the existence of a potential regime shift increase or decrease the frequency of tragedies of the commons? Can we identify social-ecological linkages that are particularly influential in determining overall outcomes? This study utilizes laboratory experiments to answer these questions.

2. Designing the experiment

The dynamics of resource renewal will play a crucial role in our experimental setting. In this section we explain in detail how we have used results from existing literature on regime shifts for our design of the ecological properties of our experimental setting. We also motivate the chosen institutional structure, provide some theoretical predictions and explain the experimental procedure.

2.1 Disentangling regime shifts

Damping and reinforcing feedback loops characterize complex systems like ecosystems and they can typically only arrange in a few ways so that the system self-organizes around one of several possible attractors (equilibrium points, limit cycles or other). A regime is then a particular domain of attraction of such system. The amount and mix of goods and services available from a particular ecosystem depend on the system's specific regime, its particular configuration in terms of structure, functions and feedbacks. Sometimes rapid and substantial reorganization in system structure, functions and feedbacks occur, entailing a radical change in the dominant system regime. Critical thresholds delimit the value of particular variables at which the system moves from one domain of attraction to another. The critical threshold for going from one regime to another often differs from the critical threshold for going back to the original regime once the system has shifted. This is called hysteresis and results from the presence of internal feedback loops that maintain the new regime, making it difficult to reverse. (Biggs et al forthcoming). Regime shifts occur for two main reasons that are often combined: a gradual change in some driver slowly weakens the dominant system feedbacks, or/and an external shock wipes out a substantial fraction of some important functions or species. These are all characteristics that we must deal with while addressing the issue of regime shifts.

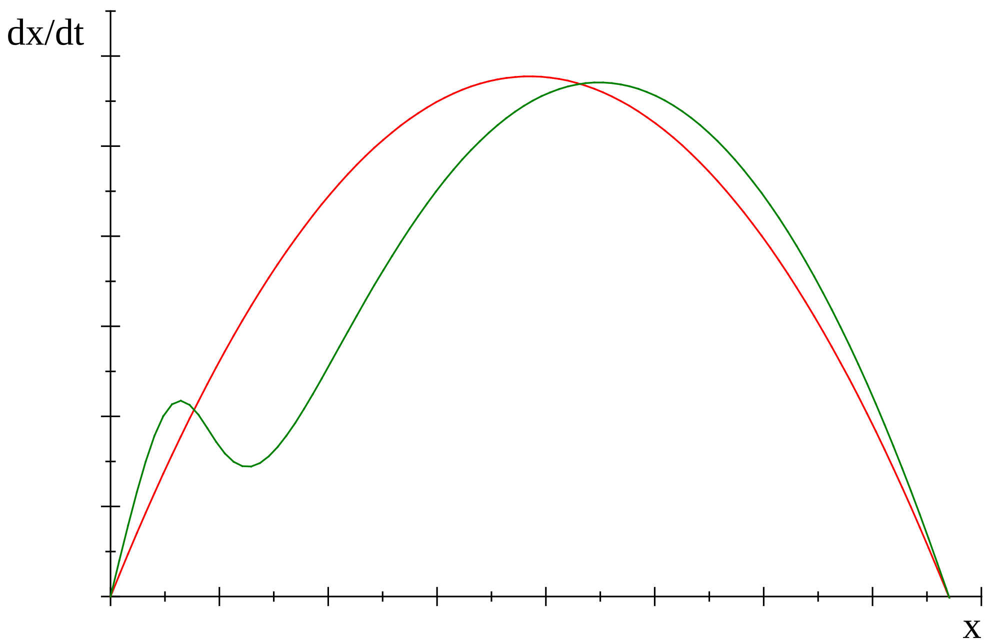
Among all the possible systems where regime shifts can occur we focus on systems producing resources that regenerate and can be harvested, thereby narrowing down the kind of systems studied but still focusing on widely studied issues where existing literature serves as a baseline for what to expect. Besides the shallow lake model that has been widely studied and discussed (Brock and Starrett, 2003; Mäler et al, 2003; Wagener, 2003), extensions of the traditional logistic model to incorporate some kind of non convexity is a relatively simple way to model regime shifts (See e.g. Crépin 2007, Crépin and Lindahl,2009, and Crépin et al 2011). The advantage of this approach is that the logistic growth model and some of its extensions have been widely used in resource economics. (Clark, 1990)

Consider a resource stock *x* at time *t* with a logistic growth with growth rate *r* and carrying capacity *K* the dynamic equation (1) represents these dynamics:

$$\frac{dx}{dt} = rx\left(1 - \frac{x}{K}\right) \tag{1}$$

The red curve in figure 1 illustrates resource growth for different levels of the stock.

Figure 1: Stock dynamics with and without potential regime shift.



Introducing the potential for regime shifts in such models is easily done by introducing a non-convexity that opens for multiple potential steady states. A simple way to go is to use the Ludwig model (Ludwig et al 1978). Equation (2) represents logistic stock dynamics with a Holling type III predation term with maximum uptake rate *b*, half saturation *a*, and exponent θ that introduces a non convexity. The green curve in figure 1 illustrates resource regrowth for different levels of the stock and a particular set of parameter values.

$$\frac{dx}{dt} = rx\left(1 - \frac{x}{K}\right) - b\frac{x^{\theta}}{a^{\theta} + x^{\theta}} \tag{2}$$

This is a quite simple model that could still fairly represent the dynamics of relatively complex systems like boreal forests, coral reefs or other kinds of aquatic systems where fish interact with floating and bottom vegetation (e.g. Ludwig et al, 1978; Scheffer et al., 2003; Crépin, 2007 and Crépin and Grass, manuscript). In this approach it is particularly relevant to focus on harvest as a particular driver for change that could potentially trigger a regime shift.

2.2 Managing resources with potential regime shifts

The management problem for a user or a group is to decide in each period how much to harvest of the resource in order to maximize the aggregated welfare derived from consumption of goods from the ecosystem. Let *h* denote harvest and *U(h,x)* the utility derived from consuming harvest and from the standing stock then a typical problem for a resource user could be formulated as follows:

$$\begin{aligned} &\max_{h\geq 0}\int_{t=0}^{+\infty} U(h,x)e^{-\delta t}dt \\ &\text{s.t.}: \frac{dx}{dt} = rx\left(1-\frac{x}{K}\right)-h \qquad \text{(a)} \\ &\text{or } \frac{dx}{dt} = rx\left(1-\frac{x}{K}\right)-b\frac{x^{\theta}}{a^{\theta}+x^{\theta}}-h \qquad \text{(b)} \end{aligned} \tag{3}$$

where (a) describes a standard “simple” resource dynamics and (b) the dynamics with a potential regime shift. This problem can be solved using Pontryagin maximum principle. Problem (3) with constraint (a) has typically one unique interior stable solution and a boundary solution where the stock gets extinct which is unstable. (See e.g. Clark, 1990.) Problem (3) with constraint (b) is more complex and may have up to three interior solutions of which two are stable and one boundary solution. The number of feasible solutions depends on parameter values. This problem is fully studied in Grass and Crépin (manuscript)

If there are *n* users *i* of the resource who own it in common property, each user’s problem would instead be formulated like this:

$$
\begin{aligned}
&\max_{h_i \ge 0} \int_{t=0}^{+\infty} U\left(h_i, x\right) e^{-\delta t} dt \\
&\text{s.t.:} \frac{dx}{dt} = rx\left(1 - \frac{x}{K}\right) - \sum_{i=1}^{n} h_i \qquad \text{(c)} \\
&\text{or } \frac{dx}{dt} = rx\left(1 - \frac{x}{K}\right) - b\frac{x^\theta}{a^\theta + x^\theta} - \sum_{i=1}^{n} h_i \qquad \text{(d)}
\end{aligned}
\qquad (4)
$$

The solution to this category of problems is harder to characterize because it will depend on the strategy of each resource user participating in the game. If they all manage to cooperate they can reach the optimal solutions, which is identical in aggregate terms to the solution of problem (3). In contrast, if the users do not manage to cooperate, things get trickier and the outcome will depend on the strategy chosen by each resource user. A Markov perfect Nash equilibrium can be calculated for simple versions of this game where all players use the same strategy (e.g. problem (4) with constraint (c) see Dockner et al. 2000, pp 331-333). Like in the optimal case there is a unique interior solution but it entails a lower steady state stock of the resource because each player tends to harvest more early. For the more complicated game (problem (4d)) we would expect multiple equilibria to occur and then it becomes difficult to calculate the final outcome because it is highly dependent on individual players' strategies (Crepin and Lindahl 2007, Mäler et al 2003, Kossioris et al), which we know little about (see introduction). The aim of this paper is to help fill this gap.

2.3 Using experiments to assess possible outcomes with regime shifts

When designing the experiments there are some restrictions to consider. The experimental setting should be easy to understand while still encompassing complex resource dynamics involving thresholds and hysteresis. Another requirement is that the experiment can be run smoothly. For example, the resource stock needs to be updated (by the experiment leader(s) several times during a limited time. Moreover, the setting should also fit within the limited research budget available to conduct the experiments and it is desirable if the setting that can be used in multiple environments ranging from classroom to field and that allows visualization of the stock if necessary (e.g with buttons, magnets or matchsticks).

To meet these demands we represent the resource growth with no regime shift as a discrete version of the logistic growth function where we introduce a minimum stock size to allow possible reproduction, here 5 units. We limit the stock size to 50 units, which is a measure of the carrying capacity. The maximum sustainable yield is then set to 9 and we let resource renewal rates change by steps of 5. Figure 2 and table 1 show the renewal rate of the resource as it is presented to the experiment participants. For the case with a potential regime shift we choose to represent the dynamics in the same way as with no regime shift for high stock levels. In both cases the maximum sustainable yield of 9 can be obtained for stock sizes between 25 and 29 units. For a stock size lower than 20 units we introduce a regime shift, where the regeneration of the resource drops dramatically. If users would like to recover a high regeneration rate it is not enough to let the stock rebuild to 20 units. Instead the user must let the stock rebuild up to 25 units or more. Figure 3 and table 2 illustrate these dynamics.

Figure 2: A graphical illustration of the resource dynamics without threshold

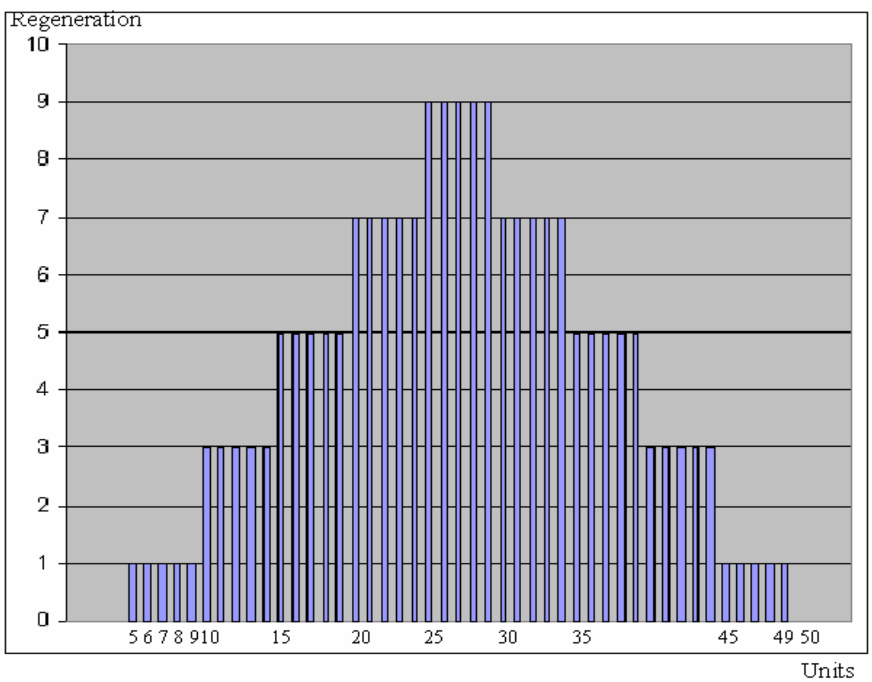


Table 1: Regeneration for each stock resource stock size when there is no threshold,

Resource stock size	Re-generation	Resource stock size	Re-generation	Resource stock size	Re-generation
50	0	32	7	14	3
49	1	31	7	13	3
48	1	30	7	12	3
47	1	29	9	11	3
46	1	28	9	10	3
45	1	27	9	9	1
44	3	26	9	8	1
43	3	25	9	7	1
42	3	24	7	6	1
41	3	23	7	5	1
40	3	22	7	4	0
39	5	21	7	3	0
38	5	20	7	2	0
37	5	19	5	1	0
36	5	18	5	0	0
35	5	17	5		
34	7	16	5		
33	7	15	5		

Figure 3: A graphical illustration of the resource dynamics with a threshold

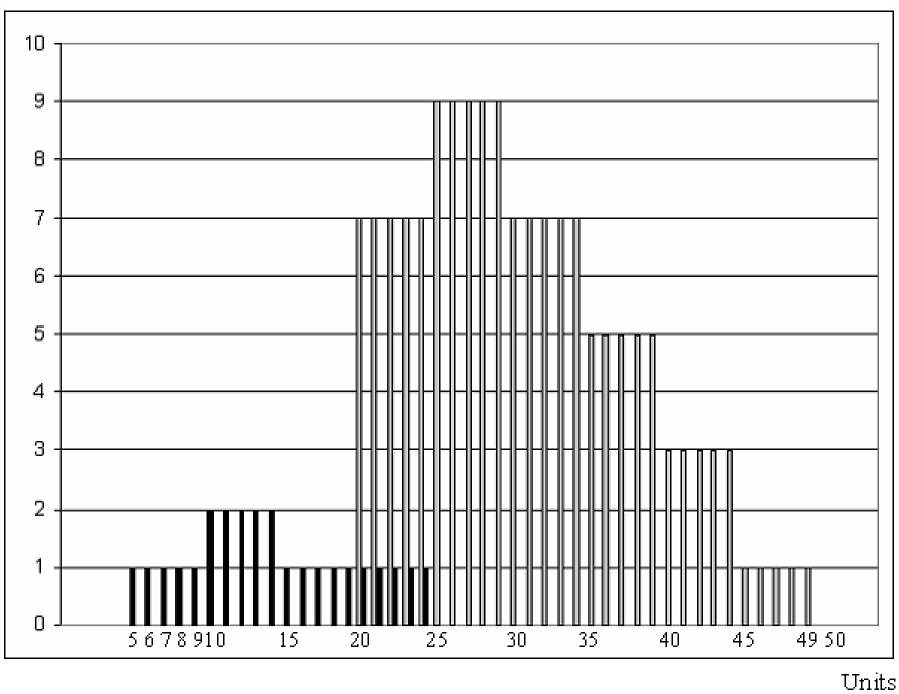


Table 2: Regeneration for each stock resource stock size when there is a threshold,

Resource stock size	Re-generation	Resource stock size	Re-generation	Resource stock size	Re-generation
50	0	32	7	14	2
49	1	31	7	13	2
48	1	30	7	12	2
47	1	29	9	11	2
46	1	28	9	10	2
45	1	27	9	9	1
44	3	26	9	8	1
43	3	25	9	7	1
42	3	24	7 alt. 1	6	1
41	3	23	7 alt. 1	5	1
40	3	22	7 alt. 1	4	0
39	5	21	7 alt. 1	3	0
38	5	20	7 alt. 1	2	0
37	5	19	1	1	0
36	5	18	1	0	0
35	5	17	1		
34	7	16	1		
33	7	15	1		

In our experiments we set the initial stock to 50 units so that each groups starts at the maximum resource stock level. With an infinite time horizon and rational resource users it is easy to verify that the optimal cooperative strategy (optimal for a single owner) is to harvest 25 units in the first round and then harvest 9 units (stay at the maximum sustainable yield) in each subsequent round. Note that this is true for both treatments. If for some reasons the resource falls lower than 25 units the optimal strategy is to let the resource grow until it again reaches 25 units (most rapid approach) and then harvest 9 units for the subsequent rounds. For non-cooperative resource users facing the management problem it is hard, if not impossible to make any predictions, especially for the resource dynamics with a potential regime shift.

We have no reasons to believe that the number of cooperating groups will differ between these two treatments or that cooperating groups will behave differently between the two treatments (we expect cooperating group to follow the optimal strategy). Even though we expect the same number of non-cooperating groups we cannot make any predictions with regard to their behavior for the two treatments.

2.5 Experimental procedure

The main focus of this experimental study is on the ecosystem dynamics. As this is the case we do not want to confuse our experimental subject with a complex institutional structure. The task will be complex enough as it is. At the same time we want to mimic the field as much as possible and be able make comparisons with earlier experimental results on common pools.

The subjects were recruited from Stockholm University. Each subject was randomly assigned to a group. In total, there were 41 groups consisting of 3-4 subjects. The experiment was carried out in May 2010 and fall 2011 at SU campus. Upon arrival, the subjects were given instructions to read (the exact instructions are available upon request from the authors), after which there was time for clarifying questions. After the actual experiment the subjects were asked to fill in a shorter questionnaire, and then received their individual payments. The whole session lasted between 60-90 minutes. None of the subjects participated in more than one session and none had previous experience of this type of experiment.

The subjects were told that they each represented a fictive resource user and that they together with the other participants in their group had access to a common resource stock. They were informed that they could harvest units of this resource, where each harvested unit was worth 5 SEK. 21 groups participated in the threshold treatment and 20 groups in the treatment without a threshold. We used examples, figures and tables to illustrate the exact resource dynamics for both treatments (see figures 1 and and 2 and tables 1 and 2 in section 2). The experiment lasted several rounds and in each round each participant took an individual decision of how many units of the resource to harvest.

"The resource regenerates itself before each new round. The regeneration depends on how much of the resource stock is left from the previous round, which in turn depends on the total harvest of the previous round (sum of your and the other participants' harvest in the previous round). As long as there are units to harvest, the experiment continues for a number of rounds."

After each round the experiment leader calculated the total harvest, lowered the resource stock by this amount, calculated how many resource units that were regenerated and disclosed the new size of the resource stock to the subjects. If the group's total harvest was equal to or exceeding the number of available resource units in one round, the resource regeneration was zero and the experiment ended. The harvest (and payment) was in that round based on each subject's percentage of the group's total harvest. (S = (harvest/total harvest)*resource stock size).

Unfortunately infinite time horizon can hardly be used in experiments so we chose to approximate an infinite time horizon by letting the exact number of experimental rounds be unknown to the subjects; they only know the maximum duration. However, we make sure to end the experiment early enough to avoid potential end game effect (harvest all in the last period). The individual decisions on how many units to harvest were communicated via protocols and were anonymous. However, the subjects were allowed to communicate orally with each other as it has been observed that in relatively small groups, appropriators often have the capability to engage in face-to face communication (Ostrom, 2006).

A questionnaire supplementing the experiments was specifically designed to identify and analyze individual attributes that may have a significant influence on the subjects' individual decisions. We asked the subject to state their age, gender, educational background (both in terms of semesters studied and discipline(s) studied). We also asked them to state on a scale from 1 to 5 how well they understood the resource dynamics. In addition to these individual attributes we asked each subject to answer how well their group managed to cooperate on a scale from 1 to 5 as well as how effective their communication was, also on a scale from 1 to 5.

3. Results

Table 3 reports descriptive statistics. 150 subjects participated in the study. About half of these participated in the threshold treatment and the other half in the no-threshold treatment. About 66 of the subjects participated in a group with 4 subjects and 34 percent in a group with 3 subjects. The average age was 29 years and about 60 percent of the subjects were female. The average reported knowledge about the resource dynamics was 4.45. The overall average cooperation index was 4.20. The average individual total earnings (excluding the show-up fee) were SEK 159.

TABLE 3: DESCRIPTIVE STATISTICS

	Mean	Std.dev	Min	Max	# obs.
Threshold (T=1, NT=0)	0.4933	0.5016	0	1	150
Prop. in a group with 4 subjects	0.6585	0.4801	0	1	150
Age	29.08	10.35	17	66	150
Female (female =1, male =0)	0.5973	0.4921	0	1	150
Knowledge of resource dynamics (scale: 1-5)	4.4533	0.9092	1	5	150
Cooperation index (scale:1-5)	4.2067	1.3625	1	5	150
Individual total earnings (SEK)	158.56	54.68	33	240	150

We first look at the overall picture of the data, comparing means and proportions of the threshold treatment with the no threshold treatment. Independent t-tests have been used to compare averages. However, experiments often lead to skew distributions, which is also the case here. According to a Kolmogorov-Smirnov test we can reject the normality assumption at the 5% level for all continuous variables of table 4. We therefore also report significance levels from non-parametric Mann-Whitney tests. To compare proportions across the two treatments, we use a contingency table Pearson's chi-square test (DÁgostino et al., 1988) All reported p-values are two-sided.

Table 4 illustrates that there is indeed some significant differences between the two treatments. Threshold groups cooperate more, achieve a higher efficiency and hence earn more money on average than groups in the no-threshold treatment. According to the independent t-test subjects in the threshold treatment are older and report a higher knowledge of the resource dynamics. This is however not the case according to the Mann-Whitney test. There are no structural differences with respect to the number of females or the number of groups with 4 subjects.

TABLE 4: COMPARING AVERAGES

	No Threshold (variance)	**Threshold (variance)**	**p-value (two-sided)**	
			t-test	**Mann-W.**
Average individual earnings per period (SEK)	10.168 (92.884)	12.883 (53.115)	0.0000	0.0000
Average achieved efficiency	0.5008 (0.1389)	0.8258 (0.0571)	0.0000	0.0000
Average cooperation index	3.8961 (2.2770)	4.5342 (1.1815)	0.0000	0.0010
Average age	28.233 (96.876)	29.883 (114.235)	0.0002	0.2750
Average knowledge of resource dynamics	4.3896 (0.9920)	4.5068 (0.6067)	0.0028	0.6040

			Pearson chi-square
Prop. of females	0.5714	0.6000	0.7210
Prop. of groups with 4 subjects	0.7237	0.7162	0.9190

Figure 4 and 5 illustrate group exploitation indexes for all 14 periods. The exploitation index has been derived from actual exploitation /current optimal exploitation, where the current optimal exploitation refers to what is optimal at a certain period given the stock size in that period. An exploitation index below 1 is thus associated with under-exploitation; and index above 1 with over-exploitation and an index equal to 1 with efficient exploitation. We have separated the threshold observations from the no-threshold observations. When there is no threshold, although some of the groups under-exploit the resource, almost half of the groups clearly over- exploit and most of these even deplete the resource.

Figure 4:

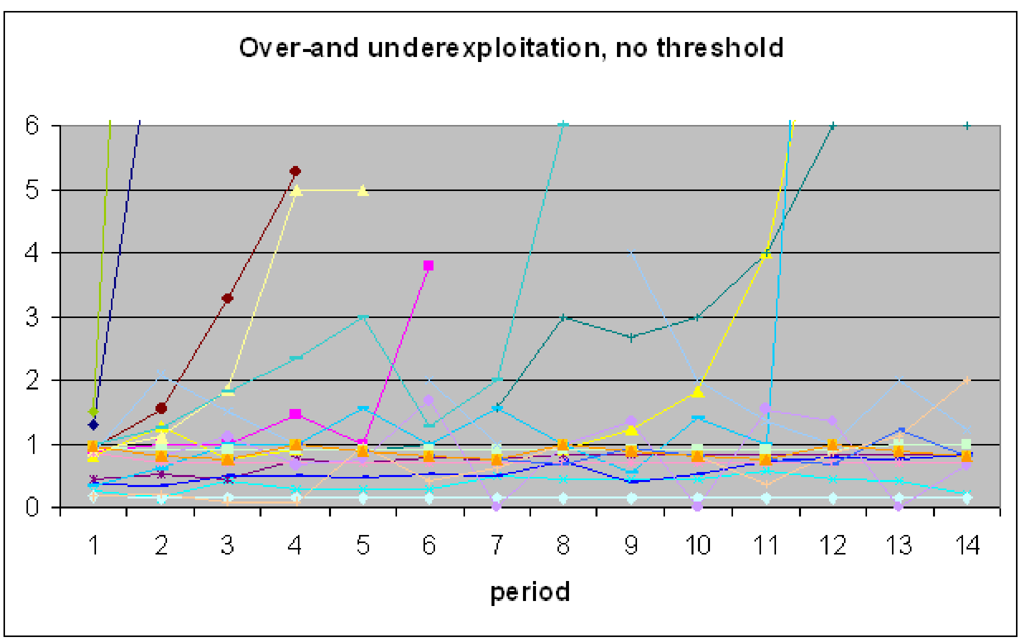
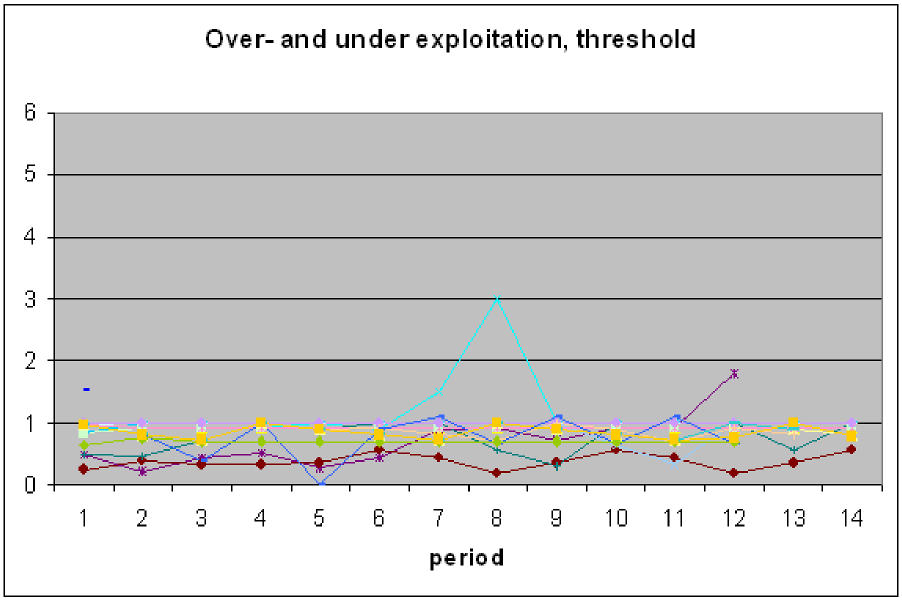


Figure 5:

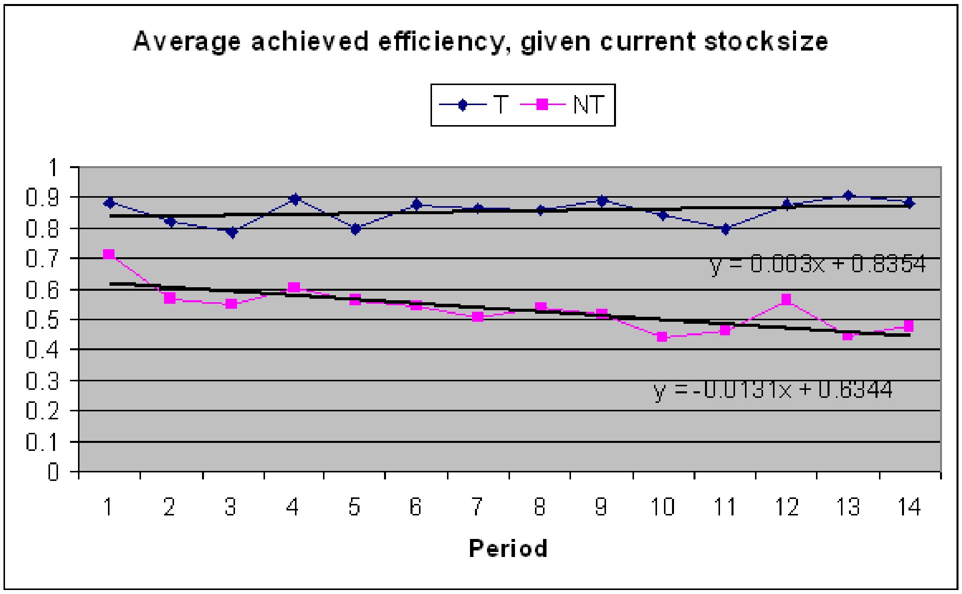


For the threshold treatment figure 5 illustrates something quite different. Almost no group over-exploits the resource; only two, of which one depletes the resource.

We have also calculated how efficient the groups were at managing the resource, where efficiency refers to ability to maximize joint earnings. We refer to current efficiency which means how efficient they are in a certain period given the stock size in that period. Figure 6 clearly demonstrates the difference between the two treatments. Groups that participated in the no-threshold treatment were not as efficient as the groups that participated in the threshold treatment.

Given the pattern illustrated in figure 4 it is not that surprising to see that no-threshold groups become less efficient over time. Once they have depleted the resource efficiency drop to zero for these groups, bringing down the average efficiency. What is surprising is that there seem to be a trend also for the threshold groups; they become more efficient with time, although the effect is economically very small.

Figure 6:



3.2 Group behavior

For some variables we have analyzed group totals or group averages, using a standard linear regression model. Table 5 reports the results from these regressions (where * denotes significance at the 10-percent level, ** on the 5-percent level and *** on the 1-percent level). The first dependent variable is total group earnings. Higher total earnings (total earnings for the group after 14 periods) should indicate that a group was more successful at managing the resource, because it implies that a group managed to sustain the resource for a long time and/or was successful to stay at the maximum level of regeneration. Groups that participated in the threshold treatment, had a higher knowledge of the resource dynamics and a higher level of cooperation earned more money on average. We have also analyzed two variables that can capture depletion; the remaining stock size after period 14 and the number of periods that were lost (periods that they could have played had they not depleted the resource). Groups that participated in the threshold treatment and groups that cooperated managed to sustain the stock for a longer time.

TABLE 5: LINEAR REGRESSION MODELS: GROUP DATA						
Dependent variables	**Total group earnings**		**End pie size**		**Lost periods**	
Variable	Coefficient (St. error)	p-value	Coefficient (St. error)	p-value	Coefficient (St. error)	p-value
Constant	34.359 (159.002)	0.8302	-11.349 (11.850)	0.3451	11.859 (2.940)	0.0003
# in group (4=1, 3=0)	-33.009 (41.697)	0.4340	-3.693 (3.108)	0.2429	0.459 (0.771)	0.5556
Threshold (T=1, NT=0)	72.138* (39.339)	0.0755	4.496 (2.932)	0.1344	-1.240* (0.727)	0.0973
Average Age	1.698 (2.549)	0.5099	0.592 (0.1900)	0.7573	-0.037 (0.047)	0.4367
Prop. Of females	-9.369 (68.103)	0.8914	5.405 (5.076)	0.2945	-1.103 (1.259)	0.3873
Group knowledge of resource dynamics	54.096* (28.360)	0.0649	-0.580 (2.114)	0.7854	-0.651 (0.524)	0.2231
Group cooperation index	59.211** (16.464)	0.0165	8.677*** (1.227)	0.0000	-1.809*** (0.304)	0.0000
Model test (F-test)	5.70	0.0004	12.76	0.0000	10.10	0.0000
Adj. R-square	0.4135		0.6381		0.5771	
# of obs.	41		41		41	

Table 6 reports the result from three regressions with efficiency as the dependent variable (where * denotes significance at the 10-percent level, ** on the 5-percent level and *** on the 1-percent level). For each group we have 14 observations (periods). We employ a random effects structure to capture potential within group correlation. In the first regression all groups are analyzed (both threshold and no-threshold groups). We see that groups that played the threshold treatment achieved on average a higher efficiency. Those groups that stated that they had a good understanding of the resource dynamics and that they managed to cooperate also achieved a higher efficiency on average. Figure 6 illustrated some trends in behavior over time. As these trends were different for the two treatments, we analyze the two treatments separately. Groups that played the threshold treatment achieved a higher efficiency if the managed to cooperate and had a higher knowledge of the resource dynamics. Efficiency is for these groups increasing with the number of periods (consistent with figure 6), indicating some form of learning.

Also, for the groups that played a classic resource dynamics game (no threshold) is cooperation significant (although not as influential). These groups perform on average less with time, with respect to efficiency (also consistent with figure 6). For these groups knowledge is not significant.

TABLE 6: RANDOM EFFECTS REGRESSION MODELS: PERIOD GROUP DATA						
Dependent variable: efficiency						
	All groups		**Groups with threshold treatment**		**Groups without threshold treatment**	
	Coefficient (St. Error)	P-value	Coefficient (st. error)	P-value	Coefficient (st. error)	P-value
Constant	-0.491 (0.266)	0.0649	-0.835 (0.903)	0.3550	0.388 (0.960)	0.6857
# in group (4=1, 3=0)	-0.065 (0.070)	0.3539	-0.011 (0.129)	0.9312	-0.279 (0.181)	0.1240
Threshold (T=1, T=0)	0.209*** (0.066)	0.0016				
Average age	0.002 (0.004)	0.5970	-0.017 (0.015)	0.2413	-0.029 (0.030)	0.3313
Prop. of females	0.059 (0.114)	0.6029	-0.881 (0.735)	0.2306	0.300 (0.030)	0.3006

Average knowledge of resource dynamics	0.111** (0.048)	0.0190	0.445*** (0.123)	0.0003	0.161 (0.183)	0.3780
Group cooperation index	0.112*** (0.028)	0.0000	0.154*** (0.054)	0.0046	0.093* (0.055)	0.0929
Ln period			0.077*** (0.002)	0.0001	-0.149*** (0.017)	0.0000
Model test (LM-test)	591.44	0.0000	163.74	0.0000	74.24	0.0000
# of observations	14*41=574		14*20=280		14*21= 294	

3.3 Individual behavior

We also look at patterns of behavior at the individual level. It is no surprise that subjects that participated in a group with only three appropriators could claim and earn more than subjects that participated in a group with four appropriators (this result is a direct consequence of the experimental design). Subjects that were in a group that managed to cooperate also could claim and earn more in total, a result which is consistent with previous group results.

There are also some other patterns of behavior. Older subjects claim and earn on average less. Moreover, those participants that state a higher level understanding of the resource dynamics earn on average less, as do females. This indicates that in a specific group, an older and/female participant is more careful than a younger and/or male participant. Similarly, in a specific group, an ignorant user can exploit his/her lack of knowledge at the expense of a more knowledgeable user.

These patterns were not picked up in the group data. Average age and the proportion of females in a group do not significantly influence the total earnings of the group and a higher average knowledge of the group is associated with a higher total group earning.

Whether a group managed to cooperate or not seems to play a crucial role for achieved efficiency and for individual and group earnings. But what triggers cooperation? The results presented in table 7 indicate that a good knowledge of the resource dynamics is also associated with a higher level of cooperation (where * denotes significance at the 10-percent level, ** on the 5-percent level and *** on the 1-percent level). Moreover, threshold groups were more likely to cooperate than groups that participated in the no-threshold treatment.

TABLE 7: RANDOM EFFECTS REGRESSION MODEL: INDIVIDUAL DATA

	Total earnings		**Total claims**		**Cooperation index**	
	Coefficient (st. error)	P-value	Coefficient (st. error)	P-value	Coefficient (st. error)	P-value
Constant	166.700 (14.821)	0.0000	35.228 (4.148)	0.0000	3.098 (0.510)	0.0000
Threshold (T = 1, NT = 0)	13.596 (8.664)	0.1166	1.630 (2.374)	0.4925	0.571* (0.320)	0.0742
# in group (4=1, 3=0)	-61.521*** (11.194)	0.0000	-11.264*** (2.945)	0.0001	-0.424 (0.407)	0.2971
Age	-0.317** (0.139)	0.0226	-0.079** (0.040)	0.0498	-0.000 (0.005)	0.9617
Female	-4.613* (2.507)	0.0658	-0.546 (0.722)	0.4499	0.101 (0.094)	0.2825
Knowledge of resource dynamics	-3.402* (1.742)	0.0508	-0.335 (0.514)	0.5144	0.242*** (0.065)	0.0002
Cooperation index	13.514*** (1.881)	0.0000	2.211*** (0.540)	0.0000		
Model test (LM-test)	78.79	0.0000	123.70	0.0000	143.36	0.0000
# observations	149		149		149	

Figure 7

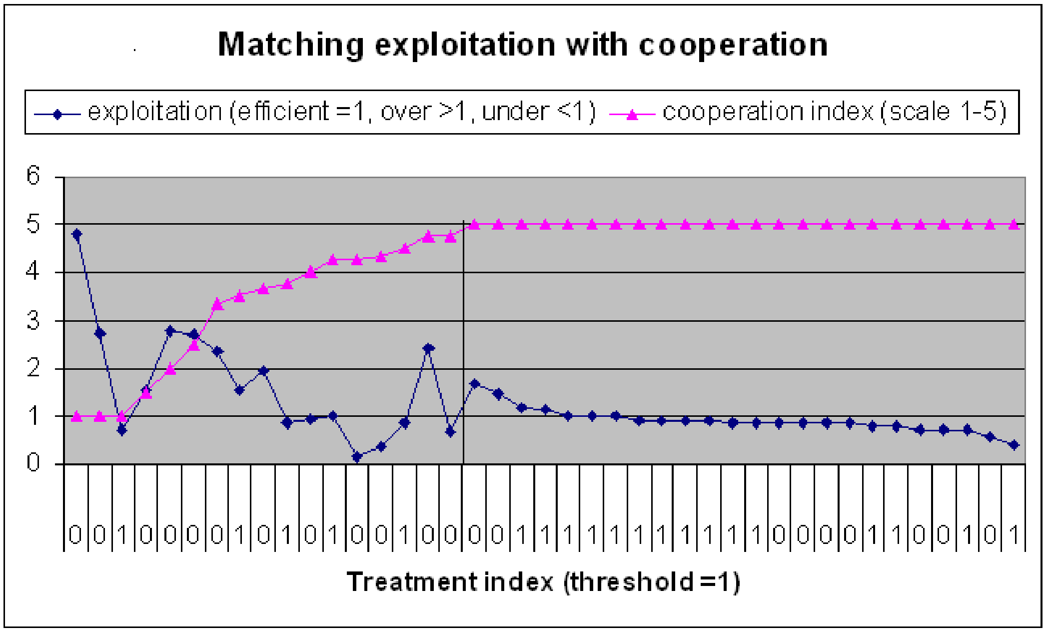


Figure 7 illustrates the match between the average exploitation and cooperation index for each group. On the x-axis the treatment index if the observations come from a threshold group (index = 1) or a no-threshold group (index = 0). The figure shows a clear correlation between high cooperation indexes and a low exploitation indexes. Moreover, of the 24 groups on the right side of the straight line (cooperative groups) 15 groups participated in the threshold treatment and 9 in the no-threshold treatment. On the left hand side only 5 of 17 groups participated in the threshold treatment. This is also illustrated in the contingency table below, where frequencies of observed values are listed. According to the Pearson's chi-square test, we should reject a hypothesis of independent columns and rows. There is link between the columns and rows, which indicates a significant pattern; threshold groups cooperate more.

TABLE 8: CONTINGENCY TABLE

	Coop. index = 5	Coop. index < 5	Total
Threshold	15	5	20
No threshold	9	12	21

Total	24	17	41
	Pearson’s chi square (observed value)	Pearson’s chi square (critical value)	p-value
	4.361	3.841	0.037
Communication index =5	13	1	14
Communication index <5	5	11	16
Total	18	12	30
	Pearson’s chi square (observed value)	Pearson’s chi square (critical value)	p-value
	11.81	3.841	0.000

We can also match cooperation index data with communication data for some of the groups (30/41). Of these about 60% of the groups reported an average cooperation index of 5 (on a scale from 1 to 5). Out of these 72% also reported an efficient communication (5 on a scale from 1 to 5). Table 8 illustrates the dependence between cooperative groups and efficient communication.

4. Discussion

The purpose of this study was to experimentally assess the effects of regime shifts on resource users’ management of common resources. We find that the existence of a potential regime shift significantly influences resource users’ strategies for cooperation and harvest decisions. Groups that face a resource generation model that entails a potential regime shift are much more likely to cooperate and obtain efficient harvest levels than groups that face a classic regeneration model. As a result these groups are also less likely to over-exploit and deplete the resource.

But what lies behind these observations? The opportunity to engage in face-to-face communication (cheap talk) where rules are not enforced by an external authority is by game theoretical predictions irrelevant. However, communication has been identified as one of the most important variable to ensure cooperative outcomes (see overviews in Kopelman et al 2002 and Ostrom 2006). This is also confirmed here. Among all underlying explanations for these results, two have been given more weight in the literature: 1) group discussions enhance group identity and solidarity and 2) group discussions foster commitments to cooperate. (Dawes et al 1990; Kopelman et al 2002) In our experiment, all groups, regardless of treatment, face the same opportunities to engage in face-to-face communication. So why don't we observe the same level of cooperation in our treatments?

Our results suggest that higher degrees of cooperation and more efficient communication are coupled with a higher degree of knowledge sharing (see Table 7). We therefore propose the following linkage as an explanation for the observed result: when groups are confronted with a threshold in the resource dynamics it is perceived as a common threat and acts as a trigger for inducing them to cooperate and communicate in order to solve and understand the problem. When they communicate and cooperate they share their knowledge with each other and become better as a group at understanding and thereby managing the resource. This kind of behavior is consistent with other experimental and theoretical findings. Santos and Pacheco (2011) show for example by using an evolutionary dynamics approach that decisions within small groups under more stringent resource conditions significantly raise the chance of coordinating actions and escaping the tragedy of the commons. It is the common threat that fosters more cooperative behavior. Moreover, Samuelsson (1991) showed experimentally that when giving the choice of assigning a leader (who alone would decide group harvest) and thereby being able to escape the tragedy, groups were more inclined to assign a leader when they though that the task before them was more difficult. However, it is not necessarily so that any kind of resource shortage could produce the same kind of behavior. Rutte et al. (1987) showed that people were more inclined to restrain the exploitation behavior for resource shortage caused by nature than by other users.

So were do we go from here? To our knowledge this has been the first experimental study designed to capture linkages between human behavior and the existence of potential regime shifts in common pool resource systems. Although we were able to provide some insights, for a more comprehensive analysis of the matter there are still many questions that need answers that we have to leave for future research. For example, what ecological characteristics and institutional factors are more or less important? It has been demonstrated that causal attributions – how a certain situation is explained - influence how much of a resource people claim for themselves. This is true also with respect to the scarcity and abundance of the resource. (Kopelman et al 2002). Therefore it could be interesting to analyze if and if so how the actual presentation of the threshold affects individual and group behavior. Such a study could have important policy implications as it could provide insights about the value of graphical illustrations as a potentially powerful mean for influencing behavior.

Of course we would also like to know how well the behavioral results represent real resource users. There are different types of experiments, ranging from laboratory experiments to natural field experiments (Harrison and List, 2004). A conventional laboratory experiment is often performed in a classroom with a standard pool of subjects (often university students) and with a neutral, context-free description of the problem. The subjects are often isolated and are not allowed to communicate with each other (unless communication is a treatment). A natural field experiment is another extreme; subjects (from a non-standard pool) take decisions in their natural environment without knowing that they participate in an experiment. A so called framed field experiment occupies the middle ground. Compared to a laboratory experiment, a framed field experiment sacrifices some of the controlled environment for increased realism (List 2006). The idea is to perform a controlled experiment that captures important characteristics of the real world. This study has used framed laboratory experiments. Our laboratory experiments employed a standard set of subjects (students) but with a real problem and resource description. These types of experiments are important for evaluating behavioral responses in the sense that a myriad of factors might influence behavior, and by progressing toward the environment of ultimate interest one can learn about whether, and to what extent, such factors influence behavior (Harrison and List, 2004). Thus, our lab experiment could serve as a crucial test-bed to evaluate the experimental design before taking it to the field.

References

Anderies, J. M., M. A. Janssen, and B. H. Walker, 2002, Grazing Management, Resilience, and the Dynamics of a Fire- Driven Rangeland System, *Ecosystems* 5(1):23-44.

Anderies, J. M., M. A. Janssen, F. Bousquet, J.C. Cardenas, D. Castillo, M.C. Lopez, R. Tobias, B. Vollan, A. Wutich, 2010, The challenge of understanding the role of context in experimental studies of common pool resource governance. *Ecological Economics.* Accepted.

ACIA, 2005, *Arctic Climate Impact Assessment*. Cambridge University Press, 1042p. http://www.acia.uaf.edu

Biggs, R., Blenckner, T., Folke, C., Gordon L. J., Norström, A., Nyström, M., and Peterson, G. D. (In press). Regime shifts. In Hastings, A. and Gross, L., (eds.) *Source book in theoretical ecology*. Berkeley: University of California Press.

Biggs, R., Carpenter S.R., Brock W.A. 2009. Turning back from the brink: Detecting an impeding regime shift in time to avert it. Proceedings from the National Academy of Sciences 106(3):826-831.

Brock, W.A. and D. Starrett, 2003, Managing systems with non-convex positive feedback, *Environmental & Resource Economics* 26:575-602.

Cardenas, J-C., M. Janssen and F. Bousquet, 2010, Dynamics of Rules and Resources: Three New Field Experiments on Water, Forests and Fisheries, in List J. and M. Price (eds.) *Handbook on Experimental Economics and the Environment*, Edward Elgar Publishing.

Carpenter, Stephen R., 2003, Regime Shifts in Lake Ecosystems: Patterns and Variation, International Ecology Institute, Oldendorf/Luhe Germany. 20.

Clark, C. W., 1990, *Mathematical Bioeconomics – The Optimal Management of Renewable Resources* Wiley and Sons.

Crépin, A.-S., 2003, Multiple Species Boreal Forests – What Faustmann Missed, *Environmental and Resource Economics* 26(4):624-646.

Crépin, A.-S., 2007, Using fast and slow processes to manage resources with thresholds, *Environmental and Resource Economics* 36:191-213.

Crépin, A.-S. and T. Lindahl, 2009, Grazing Games: Sharing Common Property Resources with Complex Dynamics, *Environmental and Resource Economics* 44:29-46.

Crépin, A-S, J. Norberg and K-G. Mäler, 2011, Coupled economic-ecological systems with slow and fast dynamics — Modelling and analysis method, *Ecological economics* 70(8):*1448-1458*

Crépin, A-S., Biggs, R., Polasky, S., Troell, M. and de Zeeuw, A. J., Regime shifts and management, submitted manuscript.

Crépin, A.-S., Grass D. *Modeling complex ecosystems – lessons from a fisheries model* manuscript

D'Agostino, R.B., W. Chase, A. Belanger, 1988, The appropriateness of some common procedures for testing the equality of two independent binomial populations. *American Statistician*, vol. 42: 198-202.

Dockner, E., Jorgensen, S., Van Long N., Sorger G., 2000. *Differential games in economics and management science*, Cambridge University Press, UK.

Hardin, G., 1968, Tragedy of the commons, *Science* 162:1243-1247.

Harrison, G. W. and J. A. List, 2004, Field Experiments, *Journal of Economic Literature* 42: 1009-1055.

Holling C.S. and G.K. Meffe, 1996, Command and control and the pathology of natural resource management *Conservation Biology* 10(2):328-337.

Janssen, M.A., R. Holahan, A. Lee and E. Ostrom, 2010, Lab Experiments for the Study of Social-Ecological Systems, *Science* 328: 613-617.

Janssen M., 2010, Introducing Ecological Dynamics into Common-Pool Resource Experiments, *Ecology and Society* 15: (issue2, article 7)

Kossioris, G., M. Plexoysakis, A. Xepapadeas, A. de Zeeuw, and K.-G. Mäler, 2008, Feedback Nash equilibria for non-linear differential games in pollution control, *Journal of Economic Dynamics and Control* 32:1312-1331.

Lenton, T.M., H. Held E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf and H. J.

Schellnhuber, 2008, Tipping elements in the Earth's climate system, Proceedings of the National Academy of Sciences, 105(6):1786-1793

Levin, S.A., 1998, Ecosystems and the biosphere as complex adaptive systems. *Ecosystems*. 1: 431-436.

List, J. A., 2006, Field Experiments: A Bridge between Lab and Naturally Occurring Data, *Advances in Economic Analysis & Policy* 6 (2): article 8.

Ludwig, D., D. Jones, and C.S. Holling, 1978, Qualitative analysis of insect outbreak systems: the spruce budworm and forest, *Journal of Animal Ecology* 47:315-332.

MA. 2005. *Millennium Ecosystem Assessment. Ecosystems and human well-being: synthesis*. Washington, DC: Island Press.

Mäler, K.-G., A. Xepapadeas, and A. de Zeeuw, 2003, The economics of shallow lakes, *Environmental & Resource Economics* 26(4):603-624.

Naevdal E., 2001, Optimal regulation of eutrophying lakes, fjords, and rivers in the presence of threshold effects *American Journal of Agricultural Economics* 83(4):972-984

Nyström M, C. Folke, F. Moberg, 2000, Coral reef disturbance and resilience in a human-dominated environment, *Trends in Ecology and Evolution* 15(10):413-417.

Ostrom E., 2006, The value-added of laboratory experiments for the study of institutions and common-pool resources. *Journal of Economic Behavior and Organization* 61:149-163.

Ostrom, E., T. Dietz, N. Dolšak, P.C. Stern, S. Stonich, S. and E.U. Weber (eds), 2002, *The Drama of the Commons*, Committee on the Human Dimensions of Global Change, Division of Behavioral and Social Sciences and Education, National Research Council.

Polasky, S., A. de Zeeuw and F. Wagener, 2011, Optimal management with potential regime shifts, *Journal of Environmental Economics and Management*. **62**(2), 229-240

Scheffer M., 2009, *Critical transitions in nature and society*. Princeton University Press, Princeton, New Jersey.

Scheffer M., S. R. Carpenter, J. A. Foley, C. Folke, and B. H. Walker, 2001, Catastrophic shifts in ecosystems. *Nature*, 413:591-596.

Scheffer M., S.H. Hosper, M.L. Meijer, et al., 1993, Alternative Equilibria in Shallow Lakes, *Trends in Ecology and Evolution* 8(8):275-279.

Steffen W., A. Sanderson, J. Jäger, P. Tyson, B. Moore III, P. Matson, K. Richardson, F. Old.eld, H.-J. Schellnhuber, T. I. B.L., and R. E. Wasson, 2004, *Global Change and the Earth System: A Planet Under Pressure*. IGBP Book Series. Heidelberg, Germany: Springer-Verlag.

Stern, N., 2006, *Review on the Economics of Climate Change*, H.M. Treasury, UK, October, . http://www.sternreview.org.uk

Van de Koppel J, M. Rietkerk and F.J. Weissing, 1997, Catastrophic vegetation shifts and soil degradation in terrestrial grazing systems *Trends in Ecology and Evolution*, 12(9):352-356

Walker B, J.A. Meyers. 2004. Thresholds in Ecological and Social Ecological Sysstems: a Developing Database. Ecology and Society, 9(2): art.3

Wagener F.O.O, 2003, Skiba Points and Heteroclinic Bifurcation Points, with Applications to the Shallow Lake System, *Journal of Economic Dynamics and Control* 27(9), 1533–1561.

Wassmann, P. and T. Lenton, eds, 2012, Special Issue: The Arctic in the Earth System Perspective - The Role of Tipping Points, AMBIO 41(1), February 2012.

Weitzman, M. (1974), Prices versus quantities, *Review of Economic Studies* 41(4):477-491.