STRATEGIC AND ENVIRONMENTAL UNCERTAINTY IN SOCIAL DILEMMAS

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Strategic and Environmental Uncertainty in Social Dilemmas

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Dissertation for the Degree of Doctor of Philosophy
Stockholm School of Economics

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Summary of Thesis

Introduction

Social dilemmas constitute a broad class of quandaries, including, for example, common pool resource (CPR) dilemmas and public good (PG) dilemmas. CPR's are characterized by non-excludability and rivalry. Each appropriator is faced with the dilemma of increasing her share of the resource, thereby risking a resource collapse, or sacrificing her own share for the benefit of the whole group. The tension between the individual and the group is often referred to as the tragedy of the commons (Hardin, 1968) and is typically associated with overexploitation. Through similar arguments, the features non-excludability and non-rivalry give rise to under-provision of PG's.

The prevalence and inefficiencies often associated with CPR's have given rise to an extensive theoretical, empirical and experimental literature with the purpose of identifying factors facilitating or frustrating CPR management. The role of resource uncertainty has not been ignored in the CPR literature. Uncertainty combined with rivalry is often said to augment users' incentive to overexploit, thereby increasing the probability of resource collapse (see, for example, Budescu, Rapoport and Suleiman, 1995a and 1995b). However, underlying most of the theoretical research is an explicit or implicit assumption of symmetric information, or a symmetric lack of information. In reality, people generally have access to different sources of information both in terms of quality and quantity, and they may differ in their abilities to process information.

In the first two papers, the assumption of symmetry is relaxed and both papers demonstrate that from a welfare perspective, the distribution of uncertainty is also of importance.

Many CPR's and PG's are natural, which can complicate the situation. In the traditional resource management literature, the exploited resource is often assumed to be properly characterized by some concave growth function. Today, there is extensive empirical evidence suggesting that many ecosystems have more complex dynamics; that is, they adapt to changes in the wider environment and often in a non-linear fashion. Growth functions are typically not concave, but rather convex-concave (Resilience Alliance, 2005; Steffen et al., 2004).

Management of such convex-concave resources can be quite challenging as the non-linear dynamics can make the ecosystem flip between alternate stable states, and even

marginal changes can cause radical transformations of such ecosystems (for an overview, see Dasgupta and Mäler, 2003).

Most of the CPR models assume the shared resource to be of fixed size or to be able to generate a constant flow of services. In Paper 3, we aim at providing a more complete picture of the overexploitation of a common resource, by combining the institutional structure of CPR management with complex ecological dynamics. We manage to raise questions and doubts about the standard assumptions.

Another feature of convex-concave resources is due to positive feedback effects; a state can become highly robust and sometimes an ecosystem change may even be irreversible. This is problematic if, for example, we wish to restore a degraded ecosystem and must decide whether to allocate resources for that purpose. The aim of paper 4 is to empirically analyze this question, by eliciting peoples' preferences through a hypothetical referendum on the issue.

Summary of Papers

Paper 1: Private Information in Common Pools
(joint with Magnus Johannesson)

We study a situation where two agents together have exclusive access to a common resource. The two agents make sequential claims on this resource, receiving their respective claims only if these are compatible. We introduce asymmetric uncertainty by letting the first player be privately informed about the size of the resource, whereas the second player only knows the probability distribution, which is common knowledge.

Conventional theory, where each player's utility depends on the own material payoffs, predicts for both information structures that the first player will claim practically the entire resource and that there will be no resource breakdowns.

To test these predictions, we run two experimental treatments, one where both agents have complete information and one where the first player has private information. The experiment reveals that there are inefficiencies and that fairness is important.

When we introduce private information, many pairs fail to coordinate. However, the probability of resource collapse does not increase, as most of the coordination failures are due to under-exploitation. Most successful coordination occurs at the even split. We propose a model to account for these findings.

Paper 2: Ignorant Exploitation of a Common Resource

The paper considers a common pool resource of uncertain size. Resource users differ with respect to the quality of their information and each user makes a decision of whether to exploit.

If agents do not differ at all with respect to knowledge, there is a classical coordination problem, associated with strategic uncertainty. However, if agents differ with respect to knowledge, the coordination problem is smaller, due to the fact that the ignorant can exploit her lack of knowledge by adopting a more aggressive strategy, at the expense of the knowledgeable agent; knowledge advantage becomes a strategic disadvantage. This result is robust and holds when actions are unobservable and simultaneous; and when actions are observable and taken in a sequential endogenous order.

An implication of this is that the more agents differ with respect to knowledge, the smaller is the probability of resource collapse and the less likely are coordination problems.

We also investigate the case where the order of moves is regulated by a public authority and show that regulation can mitigate the coordination problem by reinforcing the benefit from ignorance.

Paper 3: Grazing Games
(joint with Anne-Sophie Crépin)

There is evidence that above some critical value of grazing pressure, grasslands can flip from a grass-dominated state to an alternate state that is either woody plants-dominated or a dry desert (Resilience Alliance, 2005). Simultaneously, grasslands are often the common property of several farmers.

If grass is taken as a fixed production factor, we verify the standard result that non-cooperative farmers keep higher stock sizes and have higher grazing pressure than cooperative farmers.

We account for grassland dynamics by modeling the problem as a differential game (Dockner et al. 2002). Each farmer maximizes profits, given the dynamics of cattle and grass interaction and given the existence of multiple users. When accounting for grassland dynamics, the picture becomes more complex and the conventional result may not necessarily hold.

Paper 4: Who Wants to Save the Baltic Sea?
(joint with Tore Söderqvist)

Recent research shows that the Baltic Sea has experienced an ecosystem change and is now in a degraded state and moreover, that it is uncertain whether this deterioration is reversible. On the other hand, if no measures are taken to improve the water quality, the situation may become even worse (Swedish Environmental Advisory Council, 2005). A natural question then emerges; should resources be devoted to the purpose of restoring the Baltic Sea?

To elicit people's preferences, we design a referendum asking people to vote on a hypothetical abatement program. The purpose of the program is to improve the marine water quality of the Baltic Sea, and only with a certain probability is the program successful.

In a between-sample test, we find that the level of uncertainty has no effect on voting behavior. However, our results are mixed. The within-sample design shows

that, not only is this uncertainty characteristic significant, but it also dominates all other decision variables.

From a policy perspective, it might be crucial to know which of the two answers correctly describes people's preferences. Nevertheless, we must conclude that we cannot say who wants to save the Baltic Sea; the answer essentially depends on how we ask.

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Papers

PAPER 1

I

Private Information in Common Pools

Therese Lindahl and Magnus Johannesson

ABSTRACT. We study a situation where two agents make sequential claims on a common resource, receiving their respective claims only if these are compatible. The first player is privately informed about the resource size. If agents are selfish, theory predicts that she will claim the entire resource. An experiment refutes this prediction indicating that fairness is important. Almost all successful coordination occurs at the even split, but not all pairs succeeds. We propose a model to account for these findings.

1. Introduction

Common Pool Resources (CPR's) are characterized by rivalry in consumption and non-excludability among the users. CPR's can be natural or man-made and exist in a variety of scales from small inshore fisheries to irrigation systems and oil fields. The prevalence of CPR's and the inefficiencies often associated with them have given rise to an extensive theoretical, empirical and experimental literature devoted to investigate how different factors influence individual choices and consequently the resource. Underlying most of this research is the explicit or implicit assumption of symmetric information (or a symmetric lack of information) with respect to the characteristics of the resource. However, generally people have access to different sources of information and also differ with respect to the skill of processing this information.

In this paper we relax the assumption of symmetric information and analyze how asymmetric uncertainty influence peoples' strategies and what consequences there may be for the resource.

Our setup is the following. There are two agents who together have exclusive access to a common resource. The two agents make sequential claims and only receive their respective claims if these are compatible. By keeping the game simple we are able to

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focus solely on the effect of asymmetric information, which is the purpose of this paper. We introduce asymmetric information by letting the first player be perfectly informed about the size of the resource, whereas the second player only knows the probability distribution, which is common knowledge.

Conventional theory, where each players utility depends on the own material payoff, predicts for both information structures that the first player will claim practically the entire resource and that there will be no resource breakdowns.

To test these predictions we conduct two experimental treatments, one where both agents have complete information and one where the first player has private information. Our experimental results suggest that people have social preferences and care for fairness or reciprocity; an observation consistent with many other studies (see for example Ostrom, 2000 and Camerer, 2003 for overviews). The implication is that when both agents have complete information, the first mover advantage is mitigated. Because each user does not have exact information about the preferences of the other users, coordination failures, which often translate to resource breakdowns, occur when the first player does not scale down her claim enough.

When the first player has private information, there are two sources of uncertainty which could lead to coordination failures (uncertainty about the resource and uncertainty about the social preferences of the other player) and we find that many of the subjects do not manage to coordinate. However, most of the inefficiencies are due to under-exploitation. When we introduce one-sided uncertainty both players scale down their claims and as a result the probability of resource breakdown does not increase.

This last result is quite the opposite from results obtained in experiments with symmetric uncertainty. For example, Budescu, Rapoport and Suleiman examined the effect of symmetric uncertainty about resource size in a series of CPR dilemmas. They found that the subjects increased their claims as the level of uncertainty increases and as a result the probability of resource breakdown increased.[1] These studies only consider "selfish preferences", but conclude that when their theoretical predictions fail it can probably be explained by the existence of social preferences.[2]

Under symmetric information our game is very similar to the ultimatum game. The only difference is that the second player makes a claim in the common pool game rather than simply accepting or rejecting a proposed division. Under asymmetric information, the difference is accentuated. In ultimatum game experiments, where only

[1] A related study is also the one by Apesteguia (2001), where players could invest in a CPR market or in a private market. He tested the effect of symmetric uncertainty about the payoff function, but found no significant difference compared to complete information.

[2] See for example Suleiman and Rapoport (1988), Rapoport et al. (1993), Budescu et al. (1995a) and Budescu et al. (1995b).

the proposer knows the pie size and the responder only knows the offer the proposer makes, the private information of the proposer implies an informational advantage in addition to her first mover advantage because the responder cannot judge whether or not an outcome is fair (Croson, 1996; Kagel et al., 1996; Mitzkewitz and Nagel, 1993; Straub and Murnighan, 1995). Our experiment revealed the opposite result, as the private information significantly reduced the claim and profit of the first player. This difference in results is probably due to the fact that private information introduces a coordination problem in our setting that is absent from the ultimatum game with private information.

The reader might also recognize the resemblance to the Nash (1953) demand game. The difference is that players in the Nash demand game make their respective claims simultaneously. Fisher et al. (2003), examine experimentally an ultimatum game where with some probability the demand of the first player is hidden and the game transformed to a Nash demand game. They find that the higher the transformation probability, the lower the claims. This is consistent with our results as our subjects also scaled down their claims when faced with private information about the size of the resource. However, the coordination problem in the Fisher et al. study differs from the coordination problem in our study. In their study the size of the resource was always known, whereas there was private information about the claim of the first player.

A substantial fraction of the subjects in the experiment managed to coordinate their claims, and when they did so almost all of them coordinated on the even split. One explanation for the even-split-coordination could be that, given that people care about fairness, the even split is a focal point, in the terminology of Schelling (1960). Starting from more primitive assumptions, we show theoretically that the inequality aversion model of Fehr and Schmidt (1999) combined with a certain belief formation rule also predicts perfect coordination on the even split. One difference between these explanations is that the focality explanation only requires one round of elimination of dominated strategies, whereas the alternative explanation requires several rounds of elimination. Coordination failure may therefore arise when agents do not manage to iterate the required number of rounds, and this may be one reason for the coordination failures observed in our experiment. For so-called beauty contest games, it has been observed that subjects typically iterate only one or two rounds (Nagel, 1995; Ho, Camerer and Weigelt 1998).

The paper is organized as follows. Section 2 describes the theoretical model and the theoretical predictions based on conventional preferences. The design and results of the experiment are presented in Section 3. In Section 4 we incorporate social preferences into the model. Section 5 concludes.

2. Model

Consider two agents, agent A and agent B. These two agents have exclusive access to some divisible common resource, with rivalry in consumption. The total size of the resource is denoted x. The two agents make sequential discrete claims, r_A and r_B, on the resource, with agent A making the first claim. If the sum of both claims is less than or equal to the total size, both receive their respective claims. If the sum exceeds total size both agents receive nothing. There is perfect observability of claims. Formally, player $j's$ payoff is thus

$$p_j = \begin{cases} r_j & if \;\; r_A + r_B \leq x; \\ 0 & otherwise, \end{cases}$$

where $j \in \{A, B\}$.

2.1. Complete information. When both players have complete information the game is denoted $\Gamma_c(2)$. Under the conventional assumption that utility only depends on own material payoff, for example $U(p_j) = p_j$, we can make the following prediction.

PROPOSITION 1. *Suppose players only care about own material payoff. Then there are two Subgame Perfect Equilibria (SPE) outcomes of* $\Gamma_c(2)$; *Either agent A claims the entire resource but* ε *and agent B claims* ε, *or agent A claims the entire resource and agent B claims nothing.*

The proof of this and the following propositions are in the Appendix. Ending up with the entire resource the first player clearly has an advantage, and because the whole surplus is exploited and the probability of disagreement is equal to zero, there is efficiency.

2.2. Private information. One-sided uncertainty is introduced by letting the second player, agent B, be uncertain about the size of the resource. Agent B's (prior) belief is given by a discrete uniform probability distribution between $\underline{k}$ and $\overline{k}$, which is common knowledge. We thus have

$$x \in \left\{\underline{k}, \underline{k} + z, \underline{k} + 2z, ..., \overline{k}\right\},$$

$$f(x) = \frac{z}{\overline{k} - \underline{k} + z},$$

and

$$\mu(x) = \frac{\overline{k} + \underline{k}}{2}.$$

Introducing one-sided uncertainty transform the game into a signaling game, which we denote $\Gamma_p(2)$. The solution concept employed is now (pure strategy) Perfect Bayesian Equilibria (PBE). A PBE is a set of strategies and beliefs such that at any stage of the game, strategies are optimal given the beliefs and beliefs are derived from equilibrium strategies and observed actions using Bayes rule.

Before we state the result we need to introduce some concepts. A division is a function d from X to $\mathbb{R}_+^2$ where $X = \{\underline{k}, \underline{k}+z, \underline{k}+2z, ..., \overline{k}\}$. We denote the resulting outcome $(d_A(x), d_B(x))$. A division is called efficient if $d_A(x) + d_B(x) = x$,[3] and perfectly revealing if $d_A(x)$ has an inverse.

PROPOSITION 2. *An efficient division can be obtained as a separating PBE outcome of $\Gamma_p(2)$ if and only if it is perfectly revealing.*

A division is called strictly monotonic if $d_j(x_2) - d_j(x_1) > 0$, for all $x_2 > x_1$, where $x_1, x_2 \in X$ and $j \in \{A, B\}$. Then from Proposition 2 we obtain the following result.

COROLLARY 1. *Any efficient strictly monotonic division can be obtained as a separating PBE outcome of $\Gamma_p(2)$.*

Introducing one-sided uncertainty dramatically expands the set of possible equilibria. However, the coordination problem can be mitigated or even eliminated if a well known equilibrium refinement - Cho and Kreps (1987) intuitive criterion - is employed. The criterion puts restrictions on out-of-equilibrium beliefs according to the idea that certain types should not be expected to use certain strategies.

PROPOSITION 3. *There are two PBE of $\Gamma_p(2)$ which survive the intuitive criterion; one where agent A claims the entire resource but a fraction $\varepsilon < z$, and one where agent A claims the entire resource. Agent B claims ε and 0 respectively.*

When agents are selfish, and given that the intuitive criterion is employed, the equilibrium prediction is thus the same for both information structures. There is a clear first-player advantage, the first player, agent A claims the entire resource whereas the follower receives nothing (or the smallest discrete unit) and the probability of resource breakdown is zero.

[3] A division is feasible if $d_A(x) + d_B(x) \leq x$. Thus, an efficient division is feasible.

3. Experiment

3.1. Design. To test the predictions derived in the previous Sections 2.2 and 2.3 (Proposition 1 and 3), we consider two experimental treatments. In both treatments the size of the resource is represented by a sum of money, which is randomly drawn from a uniform discrete distribution between SEK 100 and SEK 200 with SEK 10 increments,[4] which means that

$$x \in \{100, 110, ..., 200\},$$

$$f(x) = \frac{1}{11},$$

and

$$\mu(x) = 150.$$

In Treatment 1 there is complete information about the available sum of money. Both agent A and agent B know the sum when submitting their claims. In Treatment 2 only the first player, agent A, knows the size of the available sum when submitting her claim. Again, the sum is randomly drawn from a uniform distribution between SEK 100 and SEK 200 (SEK 10 increments). Agent B does not know the size of the available sum when submitting her claim, but only knows the distribution. This is common knowledge. Claims are sequential in both treatments.

The subjects were recently enrolled to the undergraduate programme in business and administration at Stockholm School of Economics. They were paid a participation fee of SEK 40 (roughly 5.7 US dollars). The subjects were recruited to two different rooms ("Room A" and "Room B") and each subject was paired with another subject in the other room. Anonymity was maintained throughout. They were given instructions and asked to read them, after which they were given a few minutes for clarifying questions. These questions could only be asked to the experimenter privately. Each subject participated only in one of the treatments and only in a single round. In each treatment the first player (subjects in room A) submitted a claim for a sum of money available to the pair. The second player (subjects in room B) observed the claim made by person A and then submitted an own claim. If the sum of the two claims exceeded the available sum both got nothing. If the sum of the two claims was equal to or fell short of the available sum, both received their claim.[5]

[4] In US dollars this distribution would roughly be between 14 and 28 with 1.4 increments.

[5] The experimental instructions used in the two treatments are in the Appendix

3.2. Statistics. To compare average claims and profits across the two treatments we use an independent samples t-test. As experiments often lead to skewed distributions we also report the significance level with the non-parametric Mann-Whitney test.[6] We carry out these tests both for the average claim (profit) in terms of SEK and the average claim (profit) in terms of the percentage of the sum. To compare proportions across the two treatments, we use a contingency table Pearson chi-square test (D'Agostino et al., 1988). To test if the percentage claim of agent A or agent B depended on the sum, we estimated a linear regression analysis of the percentage claim as a function of the sum. We similarly tested wether the probability of resource breakdown depended on the sum, in a logistic regression analysis. All reported p-values are two-sided.

3.3. Results.

3.3.1. *Treatment 1: Complete information.* The experimental results are reported in Table 1. In the benchmark case, 94 students (47 pairs) played the complete symmetric information version of the game.

Table 1. Experimental results (standard deviation in parentheses)

	Complete information	*Private information*	*p-value of diff. (two-sided p-values)*	
			t-test	*Mann-W.*
Average A claim in SEK	88.38 (20.58)	73.80 (23.62)	0.036	0.012
Average A claim in %	55.09 (8.25)	48.93 (9.34)	<0.001	<0.001
Average A profit in SEK	72.45 (31.79)	64.52 (31.63)	0.180	0.058
Average A profit in %	48.01 (18.00)	42.38 (17.74)	0.093	<0.001
Average B claim in SEK	73.53 (27.84)	64.56 (20.46)	0.059	0.247
Average B claim in %	48.65 (13.21)	44.43 (15.17)	0.106	0.154
Average B profit in SEK	62.43 (28.33)	55.34 (27.86)	0.177	0.197
Average B profit in %	41.34 (15.87)	37.28 (18.15)	0.194	0.067
			Pearson chi-square	
Prop. of 50%-claims of A	0.49	0.62		0.143
Prop. of imitations of B	0.51	0.52		0.924
Prop. of breakdowns	0.11	0.12		0.858
Number of obs.	47	77		

The distribution of A claims can be found in Figure 1 (which is in the Appendix). Most of the agents A claimed more than half the available sum, and the average claim was about 55%. There were only three claims below half the available sum. Most

[6] Our data is skewed. According to a Kolmogorov-Smirnov test we can reject the normality assumption at the 5% level for all continuous variables in Table 1, except for the first variable in the table ("Average A claim in SEK").

claims were in the percentage range [50,70] and only 2 (4%) of the claims made by agent A were above 70 percentage. So although there was a first player advantage, this advantage was much smaller than predicted by theory.[7]

To further evaluate the results, Figure 2 and 3 (which are in the Appendix) shows the respective claims by agent B for each agent A. In both figures claims are in percentages, but in Figure 2 observations are sorted by the claim made by agent A and in Figure 3 observations are sorted by the sum. From Figure 2 we see that larger claims lead to a higher degree of resource breakdown. Thus, the second player does not accept all divisions. The overall probability of resource breakdown was 11%.

In Figure 3 it is difficult to detect any relationship between behavior and the size of the sum. This is also confirmed by the statistical tests. The percentage claim was not significantly related to the size of the sum for either agent A or agent B.[8] Consequently, the probability of resource breakdown was not significantly related to the sum.[9]

3.3.2. *Treatment 2: Private information.* In Treatment 2, 154 subjects (77 pairs) played the private information version of the game. The distribution of A claims can be found in Figure 4 (which is in the Appendix). As the figure indicates the majority, 62% (48/77), claimed exactly half the sum. Only about 10% (8/77) of the claims are for more than half the sum. A large part, about 30% (23/77) of the claims are smaller than half the sum.

From Figure 4 it is evident that the first player on average lowered her claim when we introduced one-sided uncertainty. The average claim of agent A was 49%, which is significantly lower than with complete information. Also the profit of agent A was lower with private information than with complete information. When the profit is expressed as the percentage of the sum this difference was significant at the 10% level according to both the t-test and the Mann-Whitney test. The profit in SEK was significantly different at the 10% level according to the Mann-Whitney test, but was not quite significant according to the t-test. Figure 5 and 6 (which are in the Appendix) shows the claims by agent B.

Overall about 60% (47/77) of the pairs failed to coordinate. Out of these, about 80% (38/47) was due to under-exploitation. The average percentage claim of agent B was 44% compared to 49% with complete information. The profit of agent B was also lower

[7] The first player advantage (the difference in profit between player A and player B) was significant according to the Mann-Whitney test ($p=0.043$), but not quite significant according to the t-test ($p=0.110$). When the profit was expressed as the percentage of the sum, the difference was significant at the 10% level according to both tests ($p<0.001$ with the Mann-Whitney test and $p=0.060$ with the t-test).

[8] The coefficient of the sum in a linear regression analysis was -0.024 ($p=0.520$) for claims of agent A and 0.018 ($p=0.767$) for claims of agent B.

[9] The coefficient of the sum in a logistic regression analysis was -0.009 ($p=0.561$).

with incomplete information, due to the under-exploitation. The under-exploitation also resulted in a significant first player advantage.[10]

When agent A claimed more than 50%, the probability of resource breakdown was high (see Figure 5). The overall probability of resource breakdown was 12%, which is not significantly larger than the probability of resource breakdown for the complete information case (see Table 1). In Figure 6 the claims are sorted by the available sum. As with complete information the percentage claim of agent A was not significantly related to the sum.[11] However, for agent B the percentage claim decreased significantly with the sum.[12] Despite of this, the probability of resource breakdown was not significantly related to the size of the sum.[13]

About 50% (40/77) of the players in group B imitated player A. This means that of all the subjects, 57% ((48+40)/154) played according to the even split outcome, although this did not always result in efficiency. When players managed to coordinate and avoid inefficiencies, most of them, 97% (29/30) coordinated on the even split.

While other experiments on signaling games have showed that behavior is consistent with refinements (see for example Banks, Camerer and Porter, 1994), the prediction that the first player by signaling, will claim the entire resource is clearly refuted. Instead, our results indicate that utility is not only a function of own material payoff.

There exists extensive evidence that many players are not completely selfish but they have some form of social preferences, i.e. they care for fairness or reciprocity.[14] In the next section we provide some theoretical explanations, based on fairness considerations for our results.

4. Fairness

There are many models of fairness (See for example Bolton, 1991; Kirchsteiger, 1994; Fehr and Schmidt, 1999; Bolton and Ockenfels 2000; Charness and Rabin 2002). Below we use the inequality aversion model of Fehr and Schmidt (1999). It explicitly models inferiority as well as superiority aversion, and both seem to be important in our data. To make predictions we also need to assume some underlying distribution of

[10] The difference in profit between player A and player B was significant at the 10% level according to both the Mann-Whitney test ($p=0.025$) and the t-test ($p=0.058$). This was also the case when the profit was expressed as the percentage of the sum ($p<0.007$ with the Mann-Whitney test and $p=0.080$ with the t-test).

[11] The coefficient of the sum in a linear regression analysis on claims of agent A was 0.042 ($p=0.217$).

[12] The coefficient of the sum in a linear regression analysis on claims of agent B was -0.218 ($p<0.001$).

[13] The coefficient of the sum in a logistic regression analysis was -0.014 ($p=0.226$).

[14] For an overview see Ostrom (2000) and chapter 3 in Camerer (2003).

the aversion parameters, and Fehr and Schmidt has proposed such a distribution for their model.

In the Fehr and Schmidt model people are averse both to being inferior and superior. More specifically, if claims are shares of the total size of the good, $r_j = y_j$, and the good is normalized to one, the utility of agent j can be described by;

$$U_j(.) = \begin{cases} y_j - \alpha_j \max\{y_{-j} - y_j, 0\} - \beta_j \max\{y_j - y_{-j}, 0\} \ \ if \ y_j + y_{-j} \leq 1; \\ 0 \ otherwise, \end{cases}$$

where the superiority aversion coefficient β_j lies in the interval $[0, 1]$ and the inferiority aversion parameter α_j is greater than β_j. The aversion coefficients are distributed according to the cumulative distribution functions $F(\alpha)$ and $F(\beta)$ with support $[\alpha, \bar{\alpha}]$ and $[0, 1]$. Fehr and Schmidt also provide a distribution of these aversion parameters (see Table 2).[15]

Table 2. Distributions of inequality aversion coefficients

$\alpha = 0$	*30 percent*	$\beta = 0$	*30 percent*
$\alpha = 0.5$	*30 percent*	$\beta = 0.25$	*30 percent*
$\alpha = 1$	*30 percent*	$\beta = 0.6$	*40 percent*
$\alpha = 4$	*10 percent*		

4.1. Fairness and complete information. For the complete information case this model predicts that; *i)* Agent A will claim at least half the sum, *ii)* the probability of resource breakdown will increase the higher the claim made by agent A, *iii)* claims (in percentages) will be independent of the size of the resource.[16] Our results confirm these predictions. For example our subjects were averse to being inferior as well as superior. If people only were averse to being inferior, see Bolton (1991), agent A would always claim something larger than half the sum and this was not the case for our subjects. On the contrary, our result indicates a higher average value of the superiority aversion coefficient than what earlier ultimatum game results suggests. Although we did not explicitly use words like common property/ownership in the instructions it is possible that framing the game in terms of "claims" create a sense of common ownership, leading to more generous behavior by the first player than observed in ultimatum games. Larrick and Blount (1997) found such a framing effect. With this

[15] The distribution is based on large experimental evidence on ultimatum games.

[16] We will not prove these results since they have already been derived by Fehr and Schmidt for the ultimatum game.

model coordination failures in terms of resource breakdown, when both players have complete information, arise when agent A does not scale down her claim enough.

4.2. Fairness and private information. Under the conventional assumption about preferences, the coordination problem was eliminated by employing the intuitive criterion.

REMARK 1. *Suppose players have heterogeneous inequality aversion parameters as in Fehr and Schmidt, then the intuitive criterion no longer has bite.*

Consider the example where the size of the resource is SEK 200 and the equilibrium outcome is the even split. If all agents are selfish agent A could by claiming SEK 195, signal his type and increase her payoff, which means that the even split would be eliminated by the intuitive criterion. If agents are inequality averse in line with Fehr and Schmidt this is no longer true. Suppose that agent A is selfish and claims SEK 195. According to the distribution of inequality parameters suggested by Fehr and Schmidt, the expected utility from this deviation is SEK 58.5, which is less than the payoff obtained from the even split outcome.

When we introduce one-sided uncertainty there are thus two reasons while players may fail to coordinate (uncertainty and social preferences). The experiment revealed that there were many coordination failures under incomplete information. However, when the subjects managed to coordinate, they did so on the even split. How do we explain this behavior?

Schelling (1960) argued a long time ago that there exist focal points that may resolve coordination problems.

REMARK 2. *Suppose players have heterogeneous inequality aversion parameters as in Fehr and Schmidt, then the even split is the division which maximize the sum of the utilities and this division can be obtained as a PBE outcome.*

It is easy to see from the utility specification that the even split maximizes the sum of the utilities. Moreover, if agent B has the belief that agent A will claim half the resource, and if the claim made by agent A supports this belief, the best reply for agent B is to imitate agent A, irrespective of aversion parameter. Given this response of agent B, the best strategy for agent A is then to claim half the resource. If players have social preferences and care for fairness one can therefore imagine the even split to be such a focal point.

However, the even split is a fairly extreme equilibrium outcome where the first player can neither take advantage of her position nor her private information and one can imagine other focal points depending on fairness parameters and position effects.

Consider therefore the case where agent B has the belief that agent A will make a claim to ensure her most preferred outcome, which depends on her aversion to being inferior and superior. To make predictions we need to assume some underlying distribution of aversion parameters.

Suppose that the distribution of aversion parameters is the same as suggested by Fehr and Schmidt. Even with this information, how does agent B use this information, how are the beliefs acted upon? To answer this we need to introduce an equilibrium concept which tells us how players use their beliefs about their opponent's behavior to determine their own behavior. Such a concept is the Best Reply Matching Equilibrium (BRME) introduced by Droste, Kosfeld and Voorneveld (2003), which loosely speaking is an equilibrium where players match their indivdual probability to play a certain strategy with the probability that this strategy is a best reply.[17]

Suppose that the subjects have the same underlying distribution of fairness parameters as in Table 2 and that this is common knowledge. We can then establish the following result.

PROPOSITION 4. *Suppose players have heterogeneous inequality aversion parameters as in Fehr and Schmidt, and that player B believes that player A will try to secure her most preferred division. Then the even split is the unique BRME outcome.*

Although the reply matching process "starts" with the most preferred outcome of agent A, the predicted equilibrium outcome is exactly the same as if players coordinate on the even split directly.[18] The difference between these two predictions is that only one round of iteration is needed to obtain coordination through focality whereas for the BRME more than 2 rounds of iterations is needed.

Our results indicate that several subjects were more cautious than the BRME process predicts. Insufficient iterations have been observed for "beauty contest games", first studied experimentally by Nagel (1995). In such games subjects typically manage to iterate one or two rounds (see also Ho, Camerer and Weigelt, 1998).

[17] We will omit a more formal definition of this equilibrium concept. The main features should be clear from the proof of Proposition 5, which can be found in the appendix.

[18] If players are selfish, $\alpha = \beta = 0$, and given the same belief described in Proposition 4, the BRME outcome would be the same as resulting from employing the intuitive criterion, and would only require one round of iteration.

5. Concluding remarks

Resource dilemmas have interested economists for a long time because they are often associated with inefficiencies. In this paper we have analyzed the implications of private information concerning the size of the resource. With conventional preferences private information does not affect equilibrium predictions; the first mover will claim practically the entire resource both with complete and incomplete information. As might be expected from previous experiments, we found less extreme divisions. A model with social preferences (inequality aversion) predicts some inefficiencies with complete information, as the first mover does not know how inequality averse the second player is.

Our main theoretical contribution is to show that private information about resources can mitigate the inefficiency associated with heterogeneous preferences. The need to solve the information transmission problem concerning the resource size precludes strategic use of the first mover advantage.

The experimental results showed that the first player did indeed lower her claim with private information, consistent with the above theory. There was also a strong tendency towards coordinating on the even split; most of our subjects (57%) played according to the even split and nearly all successful coordination occurred at the even split. However, many pairs also failed to coordinate, mainly due to under-exploitation. Although the risk of resource breakdown did not increase with private information, the under-exploitation resulted in an efficiency loss compared to complete information.

Our experiment was one-shot, which means that we did not consider learning effects. Learning is likely to be important for coordination, and to investigate how people coordinate it is important to study behavior both in a one-shot and in a repeated environment. However, if we were only to examine the behavior in a repetitive environment, it would be hard to separate the effect of learning from the effect of social preferences. By studying a one-shot game, we have been able to abstract from learning and show that players seem to coordinate on the even split.

In a repeated environment, it is possible that learning will drive the results towards more coordination on the even split and thereby increase efficiency. If coordination failure in the one-shot game is due to a failure to iterate the required number of rounds, learning may induce subjects to play the even split equilibrium strategy. However, these are of course only speculations and we have to leave these issues for future research.

Appendix

PROOF OF PROPOSITION 1. It is a dominant strategy for agent B to claim the remaining. If $r_A > x$, agent A would do strictly better by lowering his claim. If $r_A < x$ and if claims can be chosen continuously, there always exist a claim, r'_A such that $r_A < r'_A < x$ still leaving a positive share to agent B. However, if $r_A = x$ agent A cannot do better by lowering his claim.

Suppose claims are discrete, and that there is a smallest discrete unit, ε. If $r_A = X - \varepsilon$, agent A cannot find a larger claim still leaving a positive amount to agent B. □

PROOF OF PROPOSITION 2. Consider an efficient division, $d_A(x) + d_B(x) = x$, and suppose that agent A claims, $r_A = d_A(x)$. The claim of agent B supports this division as a PBE outcome if and only if $r_B = d_B(x) = x - d_A(x)$. Thus agent B needs to know not only the claim made by agent A, but also the size of the resource. This implies that the equilibrium must be fully separating, which means that the division must be perfectly revealing.

Suppose that $d_A(x)$ has an inverse, and that agent B has the belief that (i) agent A claims, $r_A = d_A(x)$, and (ii) that $x = \bar{k}$ if the claim made by agent A does not support this belief. The best response for agent B is to claim the remaining, $r_B = x - d_A(x)$. The best response for agent A is then to fulfill the belief and claim $r_A = d_A(x)$. For Corollary 1 note that any strictly monotonic division is perfectly revealing as it has an inverse. □

PROOF OF PROPOSITION 3. Consider any efficient separating equilibrium outcome, where $0 \leq r_A < x - \varepsilon$. If agent A of type $\bar{k}$ deviates from this equilibrium and claims $\bar{k} - \varepsilon$, that agent is the only type which could gain by doing so, given that $\varepsilon \in [0, z)$. Thus all those equilibria fail the intuitive criterion.

There are two equilibria which survive the intuitive criterion. Consider first the equilibrium where agent A claims $x - \varepsilon$ and agent B claims the remaining, ε. If the agent A with type $\bar{k}$ deviates from this equilibrium and claims the entire resource it is not a strict dominant strategy for agent B to claim nothing which means that agent B cannot be certain that the deviation is by an agent A of type $\bar{k}$, and thus this strategy cannot be eliminated by the criterion. If Agent A claims the entire resource in equilibrium, none of the types would gain by deviation. □

To prove Proposition 4 we first need to establish that if players know the distribution of the aversion parameters they also know the distribution of preferred equilibrium outcomes. Fehr and Schmidt derive the result that every player B has a specific threshold requirement, $\hat{y}_B(\alpha_B)$, which depend on her inferiority aversion parameter. Given our specification, this threshold is given by $\hat{y}_B(\alpha_B) = \alpha_B/(1 + 2\alpha_B)$. Consider

two such thresholds for two aversion parameters, α'_B and α''_B where $\alpha''_B > \alpha'_B$, which implies that $\hat{y}_B(a'_B) < \hat{y}_B(a''_B) < 0.5$. The proportion of players B supporting the PBE outcome $\{y_A, y_B\} = \{(1-\hat{y}_B(a''_B)), \hat{y}_B(a''_B)\}$ equals $F(\alpha''_B)$ and the proportion of players B supporting the PBE outcome $\{(1-\hat{y}_B(a'_B)), \hat{y}_B(a'_B)\}$ is $F(a'_B) = F(\alpha''_B) + p'_B$, where p'_B is the proportion of players B with an inequity aversion coefficient exactly α'_B. So for a specific range of PBE outcomes, $[\{(1-\hat{y}_B(a'_B)), \hat{y}_B(a'_B)\}, \{(1-\hat{y}_B(a''_B)), \hat{y}_B(a''_B)\})$, the proportion of players that can support those outcomes remains constant and is equal to $F(a''_B)$.[19]

For player A, as long as the sum of claims does not exceed the available resource size, marginal expected utility of the share, $\frac{\partial EU_A}{\partial y_A} = 1 - 2\beta_A$, is increasing for all $\beta_A < 0.5$. This means that of all the candidates in the specified range, a player A with $\beta_A < 0.5$, prefers the division where she ends up with the higher share, $\{(1-\hat{y}_B(a'_B)), \hat{y}_B(a'_B)\}$. Now comparing this division with the other candidate, $\{(1-\hat{y}_B(a''_B)), \hat{y}_B(a''_B)\}$, there exists a critical $\hat{\beta}_A$ where this other candidate is preferred.

LEMMA 1. *i) A player A with a superiority aversion coefficient $\beta_A \in [0, 0.5]$ strictly prefers the outcome $\{(1-\hat{y}_B(a''_B)), \hat{y}_B(a''_B)\}$ to the outcome $\{(1-\hat{y}_B(a'_B)), \hat{y}_B(a'_B)\}$ if $\beta_A < \hat{\beta}_A$, where $\hat{\beta}_A$ is defined by*

$$\hat{\beta}_A = \frac{(1+2\alpha'')F(\alpha')(1+\alpha') - (1+2\alpha')F(\alpha'')(1+\alpha'')}{[(1+2\alpha'')F(\alpha') - (1+2\alpha')F(\alpha'')]}.$$

(ii)A player A with a superiority aversion coefficient $\beta_A \in (0.5, 1]$ strictly prefers the outcome $\{0.5, 0.5\}$.

PROOF OF LEMMA 1. The weak inequality

$$EU_A(y_A = (1-\hat{y}_B(a''_B))) \geq EU_A(y_A = (1-\hat{y}_B(a'_B)))$$

holds if and only if

$$F(a''_B)\left(\frac{1+\alpha''_B-\beta_A}{1+2\alpha''_B}\right) \geq F(a'_B)\left(\frac{1+\alpha'_B-\beta_A}{1+2\alpha'_B}\right),$$

which holds if and only if

$$\beta_A \geq \frac{F(a'_B)(1+\alpha'_B)(1+2\alpha''_B) - (1+2\alpha'_B)F(a''_B)(1+\alpha''_B)}{(F(a'_B)(1+2\alpha''_B) - (1+2\alpha'_B)F(a''_B))}.$$

□

PROOF OF PROPOSITION 4. Suppose that player B believes that player A will play according to her most preferred outcome. Lemma 1 describes the distribution of player A's preferred outcomes. Player B forms a best response to this distribution. Player A

[19] Note that the division$\{\hat{y}_B(\alpha''_B), (1-\hat{y}_B(\alpha''_B))\}$ is not included in the range.

can then update her belief about responder behavior and form an optimal response. This process will continue until players reach a BRME. We now iterate the necessary steps.

Given the distribution of aversion parameters suggested by Fehr and Schmidt, the maximum share player A could get given the the set of critical thresholds, $y_A = (1 - \hat{y}_B(\alpha_B))$, with respective support, $F(\alpha_B)$, and expected utility, $EU_A(\beta_A)$, from playing according to these divisions is given by;

y_A	$F(\alpha_B)$	$EU_A(\beta_A)$	$EU_A(0)$	$EU_A(0.25)$	$EU_A(0.6)$
1/2	$F(4) = 1$	0.5	0.5	0.5	**0.5**
5/9	$F(4) = 1$	$1/9(5 - \beta_A)$	0.556	**0.528**	0.49
2/3	$F(1) = 0.9$	$9/30(2 - \beta_A)$	**0.6**	0.525	0.42
3/4	$F(0.5) = 0.6$	$6/40(3 - \beta_A)$	0.45	0.413	0.36
1	$F(0) = 0.3$	$1/3(1 - \beta_A)$	0.33	0.25	0.13

Thus of all players A, those with $\beta = 0.6$, prefer the equal share equilibrium, and those with $\beta = 0.25$ prefer the outcome $y_A = 5/9$. Finally, players A with $\beta = 0$ prefer $y_A = 2/3$. Given this information, if player B believes that the A-population will play accordingly, then the expected utility for different equilibrium outcomes is given by;

y_B	$EU_B(\alpha_B)$	$EU_B(0)$	$EU_B(0.5)$	$EU_B(1)$	$EU_B(4)$
y_A	$0.4y_A$	$0.4y_A$	$0.4y_A$	$0.4y_A$	$\mathbf{0.4y_A}$
$4/5y_A$	$0.14y_A(4 - \alpha_B)$	$\mathbf{0.56y_A}$	$\mathbf{0.49y_A}$	$\mathbf{0.42y_A}$	0
$1/2y_A$	$0.5y_A(1 - \alpha_B)$	$0.5y_A$	$0.25y_A$	0	< 0

A player B with $\alpha = 4$ wants to imitate player A. The remaining types of player B want to go for the outcome where $y_B = 4/5y_A$. For player A, the expected utility from the different equilibrium outcomes is then given by;

y_A	$F(\alpha')$	$EU_A(\beta_A)$	$EU_A(0)$	$EU_A(0.25)$	$EU_A(0.6)$
0.5	1	0.5	**0.5**	**0.5**	**0.5**
5/9	0.9	$0.1(5 - \beta_A)$	**0.5**	0.475	0.44

Only players with $\beta_A = 0$ are indifferent between claiming 5/9 and claiming half. The remaining wants to claim half. Then if the BRME assigns equal weight, 15 percent claims 5/9 and the remaining claims half. Then expected utilities for player B is given by;

y_B	$EU_B(\alpha_B)$	$EU_B(0)$	$EU_B(0.5)$	$EU_B(1)$	$EU_B(4)$
y_A	$0.85y_A$	$\mathbf{0.85y_A}$	$\mathbf{0.85y_A}$	$\mathbf{0.85y_A}$	$\mathbf{0.85y_A}$
$4/5y_A$	$0.15\frac{1}{9}y_A(4 - \alpha_B)$	$0.15\frac{4}{9}y_A$	$0.15\frac{2}{63}y_A$	$0.05y_A$	0

For all players B it is a best reply to imitate player A, which means that the best response for player A is to claim exactly half the resource. □

Instructions

The original instructions were in Swedish. This appendix reprints a translation of the instructions used in the two experimental treatments; the complete information case and the private information case.

Instructions, complete information

Thank you for agreeing to participate in this experiment. As a compensation for participating you (and the other participants in the experiment) will receive SEK 40. This compensation of SEK 40 plus the profit you make during the experiment will be paid towards the end of the experiment.

In this experiment each of you will be paired with another person who is in another room. Neither of you will be told who the other person is either during or after the experiment. There is the same number of persons in each room (A and B) **This is room A (B)**. Every person in room A and B has been given these instructions and a number that shows which pair they belong to.

Each pair will decide how to divide a sum of money. The sum of money available to each pair varies between SEK 100-200. One of the following 11 sums have randomly been distributed to your pair (with equal probability for each sum) SEK; 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200. The sum available to your pair is written on the form called "sum" which has been distributed to both the person in room A and to the person in room B.

At stage 1 the person in room A makes a claim of the sum. The person is room B will be informed about this claim and will then also make a claim. The experiment has two possible outcomes.

(i) If the sum of your and your partner's claim exceed the available sum both get nothing.
(ii) If the sum of your and your partner's claim is equal to or falls short of the available sum both receive their respective claims.

The experiment is carried out the following way. At stage 1 the person in room A writes down her claim on the form called "claim" (which has been distributed to every person in room A). The experimenter then collects this form and hands it out to the person in room B. At stage 2 the person in room B writes down her claim on the same form. The form is then collected and handed out to the person in room A.

In the protocol both persons note the outcome of the experiment; their own claim, the other person's claim, the available sum, and the own profit of the experiment. Every person then receives their profit of the experiment plus the SEK 40 participation fee.

Instructions, private information

Thank you for agreeing to participate in this experiment. As a compensation for participating you (and the other participants in the experiment) will receive SEK 40. This compensation of SEK 40 plus the profit you make during the experiment will be paid towards the end of the experiment.

In this experiment each of you will be paired with another person who is in another room. Neither of you will be told who the other person is either during or after the experiment. There is the same number of persons in each room (A and B) **This is room A (B)**. Every person in room A and B has been given these instructions and a number that shows which pair they belong to.

Each pair will decide how to divide a sum of money. The sum of money available to each pair varies between SEK 100-200. One of the following 11 sums have randomly been distributed to your pair (with equal probability for each sum) SEK; 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200. The person in room A knows the exact sum that has been assigned to her pair (it is written on the form called "sum" and every person in room A has received one). The person in room B does not know the sum, but only that the probability of each possible sum between SEK 100-200 is equally large.

At stage 1 the person in room A makes a claim of the sum. The person is room B will be informed about this claim and will then also make a claim. **(Note that the person in room B makes this claim without knowing the exact available sum)**. The experiment has two possible outcomes.

(i) If the sum of your and your partner's claim exceed the available sum both get nothing.
(ii) If the sum of your and your partner's claim is equal to or falls short of the available sum both receive their respective claims.

The experiment is carried out the following way. At stage 1 the person in room A writes down her claim on the form called "claim" (which has been distributed to every person in room A). The experimenter then collects this form and hands it out to the person in room B. At stage 2 the person in room B writes down her claim on the same form. The form is then collected and handed out to the person in room A. At the same time each person in room B opens the closed envelope, which has been distributed to every person in room B and is thereby informed about the sum that was available to

her pair. Before the person in room B opens the envelope she should also write down her estimate of the sum available to her pair.

In the protocol both persons note the outcome of the experiment; the own claim, the other person's claim, the available sum, and the own profit of the experiment. Every person then receives their profit of the experiment plus the SEK 40 participation fee.

Protocol

Claim made by the **person in room A** SEK .....
Claim made by the **person in room B** SEK .....
Available sum of money for **your pair** SEK .....

Your profit from the experiment SEK .....*

(If the sum of your and your partner's claim exceed the available sum your profit is SEK 0. If the sum of your and your partner's claim is less than or equal to the available sum your profit is equal to your claim.)

* Note that every person participating in the experiment, both in room A and room B, except for the profit also receives a participation fee of SEK 40.

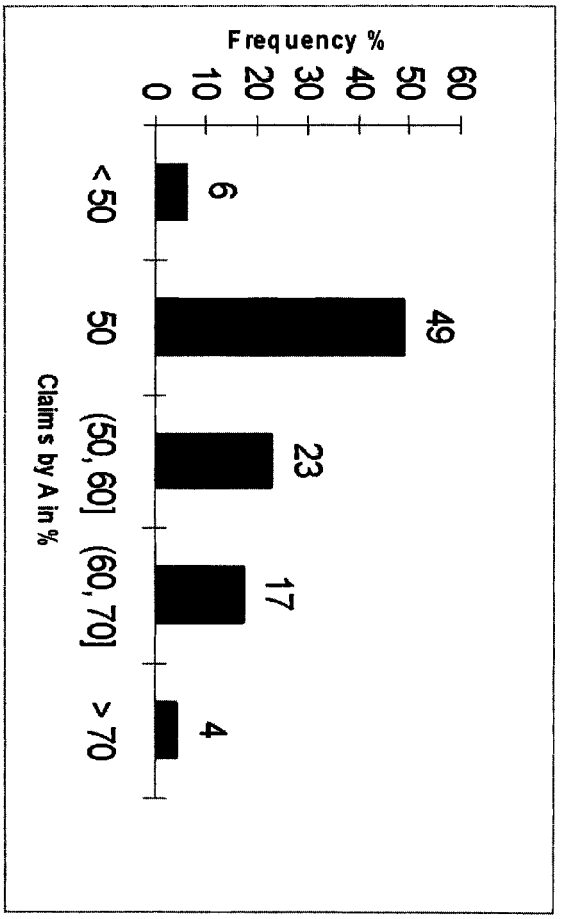

FIGURE 1. Distribution of Aclaims, complete information

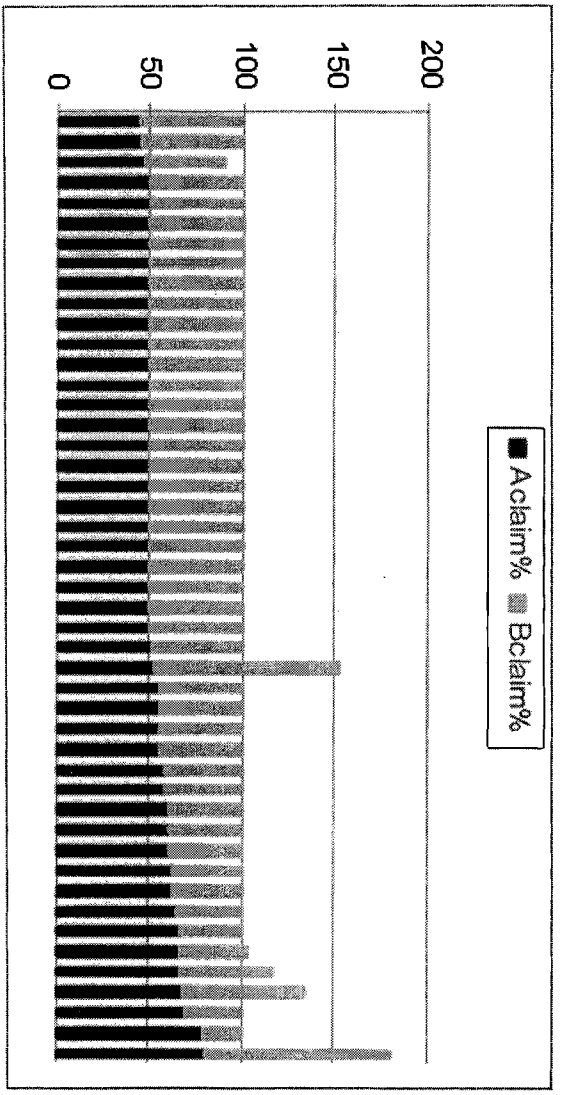

FIGURE 2. Sums of claims (%), complete information (sorted by Aclaim%)

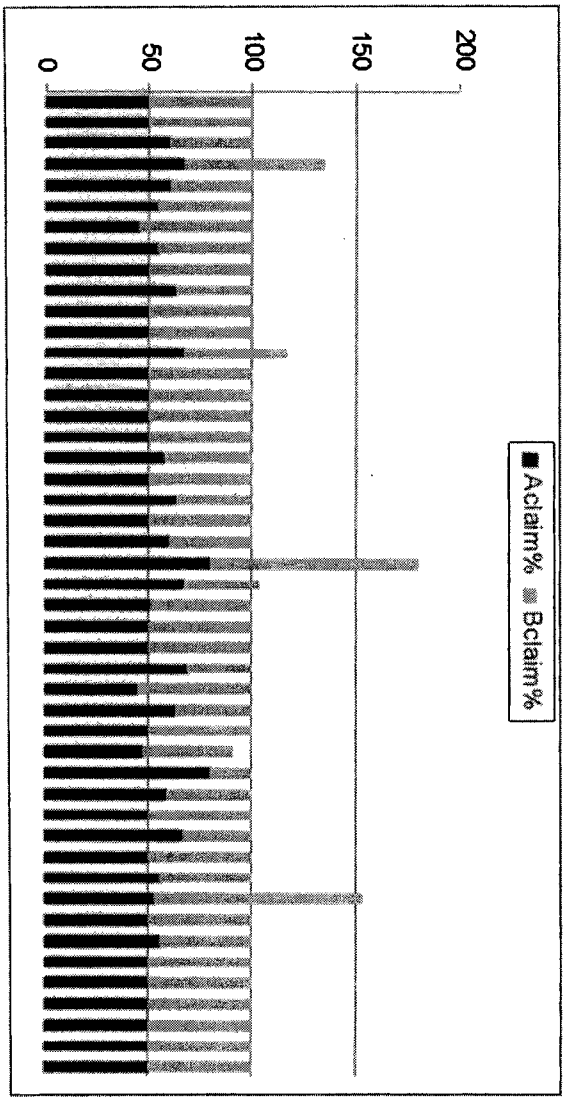

FIGURE 3. Sums of claims (%), complete information (sorted by sum)

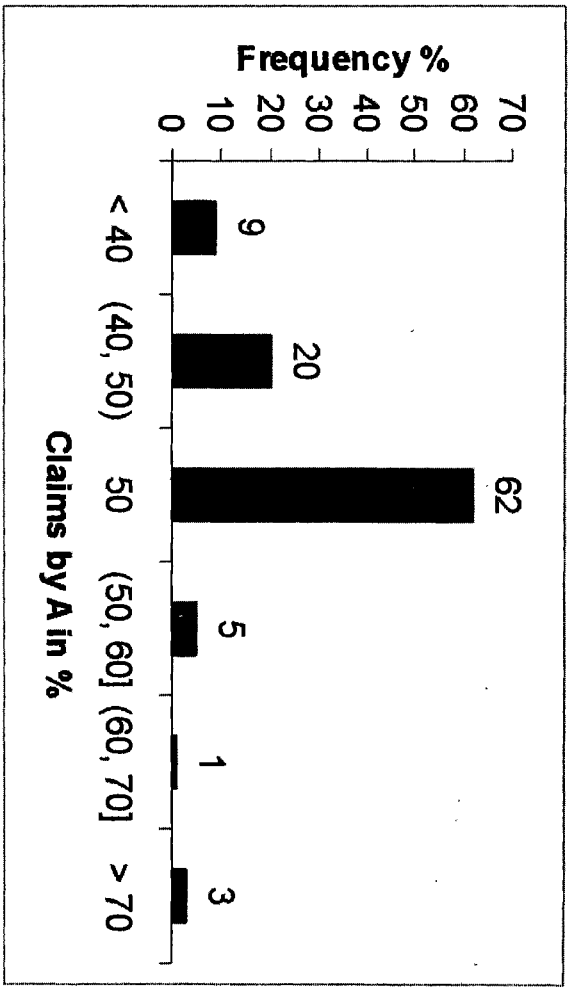

FIGURE 4. Distribution of Aclaims, private information

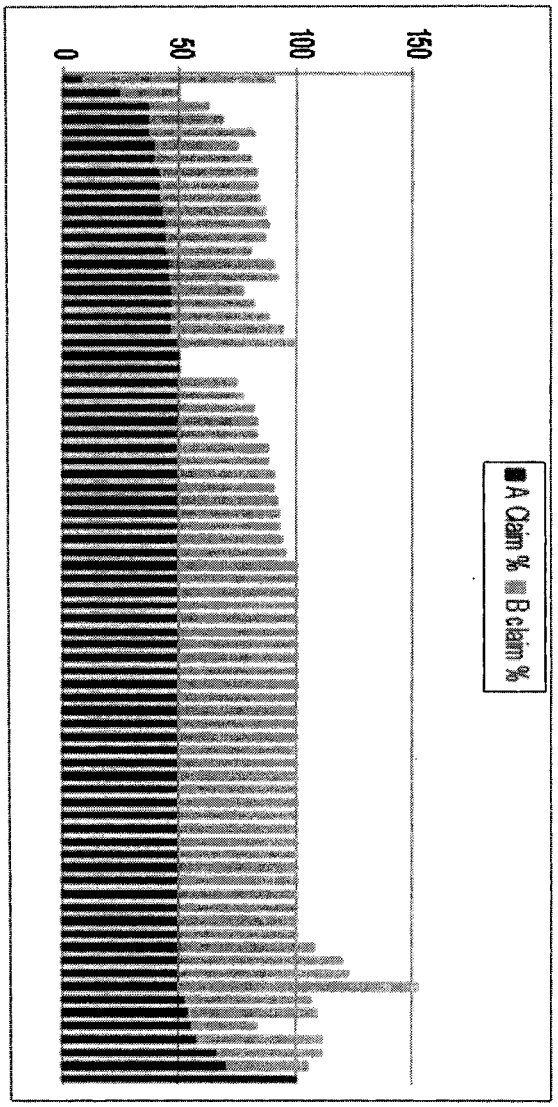

FIGURE 5. Sums of claims (%), private information (sorted by Aclaim%)

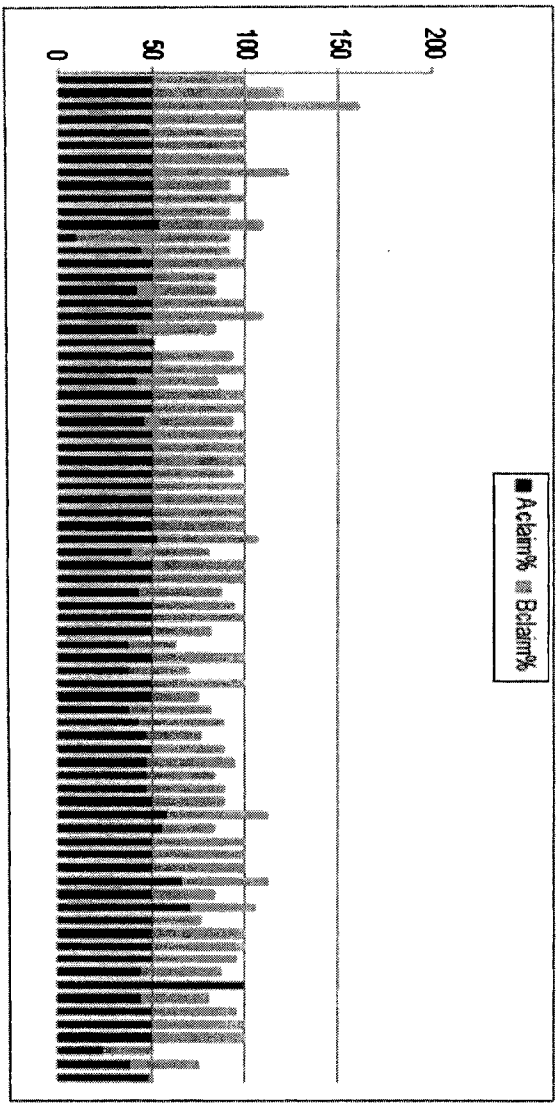

FIGURE 6. Sums of claims (%), private information (sorted by sum)

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PAPER 2

Ignorant Exploitation of a Common Resource

Therese Lindahl

II

ABSTRACT. The paper considers a common pool resource of uncertain size. Resource users differ with respect to the quality of their information. We show that the ignorant agent can take advantage of her lack of knowledge at the expense of the knowledgeable agent. Knowledge advantage becomes a strategic disadvantage. Moreover, the more agents differ with respect to knowledge, the smaller is the probability of resource collapse and the less likely are coordination problems.

1. Introduction

Consider a group of users with exclusive access to a common pool resource (CPR). In CPR games each appropriator is confronted with the dilemma of increasing her share of the resource, thereby risking resource degradation or even a resource collapse, or reducing her share for the benefit of the whole group. The tension between the interest of the individual and the group has been labeled the *tragedy of the commons* (Hardin 1968).

Many CPR's are natural. This could exacerbate the tragedy, because in natural resource management it is often difficult to determine the exact size or carrying capacity; the size of many natural resources is uncertain. There have been numerous contributions to the CPR literature and the specific effect of resource uncertainty has not been ignored (see for example Suleiman and Rapoport 1998). However, existing theoretical work has focused on the case of symmetric information. In reality, people tend to have different information, both in terms and quantity and quality, i.e. they differ with respect to knowledge. In a rivalry setting, agents may have incentive to use their knowledge strategically, which could have consequences for overall welfare.

The main purpose of this paper is to analyze the strategic interaction between asymmetrically informed agents.

[0] I am grateful to Tore Ellingsen for many valuable comments. This paper also benefited from discussions at the Tenth Ulvön Conference on Environmental Economics and from seminar discussions at the Beijer International Institute of Ecological Economics.

The model considers two agents with exclusive access to a common resource. Exactly how many appropriators this resource can sustain is uncertain but each agent has private information, of different quality, about the matter. Each makes an independent decision whether or not to exploit. We consider both simultaneous and sequential exploitation decisions.

Throughout the paper, we have considered the case of two agents sharing a CPR. However, given the simplicity and generality of the setup, the results should also hold for other types of coordination problems. Consider for example two firms contemplating incurring sunk cost and enter a market, where the number of firms that the market can sustain is uncertain. One can also think of the mirror image of the CPR problem, public good provision where the provision threshold is uncertain. Another classic example is two agents bargaining over a resource, where the value of outside option, should a disagreement take place, is unknown.

For simultaneous exploitation there are mainly two outcomes. If agents do not differ at all with respect to knowledge there is a classical coordination problem. However, if agents differ with respect to knowledge, the coordination problem is smaller, due to the fact that the ignorant can exploit her lack of knowledge, by adopting a more aggressive strategy, at the expense of the knowledgeable agent; knowledge advantage becomes a strategic disadvantage. This result is robust and holds when actions are unobservable and simultaneous; and when actions are observable and taken in a sequential endogenous order.

We also investigate the case in which the order of moves is regulated by a public authority and show that regulation can mitigate the coordination problem by reinforcing the benefit from ignorance.

Uncertainty combined with rivalry is often said to augment users' incentive to overexploit, thereby increasing the probability of resource collapse. For example, Rapoport, Budescu and Suleiman (1993) analyze a resource dilemma where resource uncertainty is modeled by letting resource size be uniformly distributed. Experimental findings consistent with their theory are that the requests of the users increase when the resource size gets more uncertain. (Budescu et al. 1995a; Budescu et al. 1995b). This paper demonstrates that the distribution of uncertainty matters too. The more appropriators differ with respect to knowledge, the smaller is the probability of resource collapse.[1]

[1] This result is similar to the result found by Bolton and Farrell (1990). In their model two firms have the opportunity to enter a natural monopoly market, a setup typically associated with a coordination problem. They show that the more firms differ with respect to sunk cost, the less likely is excess entry.

Although the conventional result in bilateral relations with asymmetric information is that the informed part has an advantage over the uninformed, other "ignorance-is-bliss results", have been found in principal-agent frameworks. For example, Cremér (1995) shows that lack of information works as a credible threat in inducing the agent to work harder. Kessler (1998) demonstrates that in procurement with adverse selection, an uniformed agent is better of in equilibrium than an agent with complete information.

The remainder of this paper is structured as follows. The model is introduced in Section 2. The results derived for unregulated agents are presented in Section 3, and for regulated agents in Section 4. Final remarks are given in Section 5.

2. The model

Two agents contemplate exploiting a common resource. If an agent decides to exploit she will face an investment cost, a sunk cost, denoted C. There are two states of the world, $X \in \{G, B\}$. If the state is good, (G), the net payoffs for the two agents are given by the matrix

	Exploit	Stay out
Exploit	$(1,1)$	$(\pi^m, 0)$
Stay out	$(\pi^m, 0)$	$(0,0)$

where $\pi^m \geq 1$. If the state is bad (B), payoffs are

	Exploit	Stay out
Exploit	$(-C,-C)$	$(\pi^m, 0)$
Stay out	$(0, \pi^m)$	$(0,0)$

where $C \in (0,1]$. The agents do not know the true state but they share a common prior probability, $\rho = 0.5$, that the state is good. The two agents also have access to private information in the form of signals. There are two signals $\Sigma = \left\{\sigma^B, \sigma^G\right\}$. When the signal σ^B $\left(\sigma^G\right)$ is observed it means that some kind of information has been observed indicating that the true state is bad (good). I will refer to such a signal as a *bad* (*good*) signal. Let $j \in \{I, K\}$ denote whether an agent is ignorant (I) or knowledgeable (K). Signals are drawn independently from a state dependent distribution satisfying:

$$\Pr\left[\sigma^G \mid G,\ j\right] = \Pr\left[\sigma^B \mid B,\ j\right] = q_j$$

and

$$\Pr\left[\sigma^G \mid B,\ j\right] = \Pr\left[\sigma^B \mid G,\ j\right] = 1 - q_j,$$

where $1 > q_K > q_I > 0.5$. In the analysis it will be convenient to use the two variables

$$k_j = \frac{q_j}{(1 - q_j)}$$

and

$$i_j = \frac{(1 - q_j)}{q_j}.$$

We shall refer to k_j as the knowledge of agent j and to i as the ignorance of agent j. Note that knowledge is strictly increasing in q_j, and defined on the interval $(1, \infty)$, whereas ignorance is defined on the interval $(0, 1)$. Also note that if the sunk cost, C, is low enough, exploitation is a dominant strategy. From now on, we thus assume that $C \in (i_K, 1]$.[2]

It is important to realize that although signals are private information the agents do know the quality of each other's signals and this is common knowledge.

In the analysis we will make a distinction between observable and unobservable actions and we will focus on pure strategies. If actions are unobservable the game will be a simultaneous move game and the solution concept is Bayesian Nash Equilibrium (BNE). If actions are observable agents may take their actions in a sequential ordering and the game will be extended to two periods. Since the agents do not know each other's signals, the start of the game does not form a proper subgame until posterior beliefs have been specified and therefore we cannot test whether the continuation strategies are Nash equilibrium. This implies that players' beliefs about other players' actions must be specified as part of the equilibrium. The solution concept employed is Perfect Bayesian Equilibrium (PBE).

3. Unregulated appropriators

3.1. Unobservable actions - simultaneous moves. The simultaneous move game is denoted $\Gamma_u(2)$. For future reference we will denote the strategy *exploits only after observing a good signal* as *following signal.* Thus, each player chooses among four strategies; *always exploit*, *never exploit*, *follow signal* and *oppose signal.*

[2] If $C \leq i_K$, there is no conflict because for both agents it is true that it is a dominant strategy to exploit after observing a bad signal, even if the other agent also decides to exploit, because the expected utility $(1 - q_j) - q_j C$ is greater than zero.

PROPOSITION 1. *The pure strategy BNE outcomes of* $\Gamma_u(2)$ *are:*
(i) If $i_K < C \leq i_I$, *{the knowledgeable follows signal, the ignorant always exploits};*
(ii) If $i_I \leq C \leq 1$, *{the knowledgeable follows signal, the ignorant always exploits} and {the knowledgeable always exploits, the ignorant follows signal}.*

PROOF. See the Appendix □

If sunk cost is in the range of case (i), the knowledgeable agent follows signal whereas the ignorant always exploits. If the ignorant observes a bad signal, she does not put too much weight on this information for two reasons. First there is a large enough probability that it is the wrong signal, secondly, if it is the correct signal she knows that there is a probability that the knowledgeable also receives a correct signal and chooses not to exploit.[3] *Thus the ignorant can take advantage of her lack of knowledge and the knowledge advantage becomes a strategic disadvantage.* Note that the more agents differ with respect to knowledge the larger is the range of sunk cost values where the ignorant can exploit her lack of knowledge.

Consider next case *(ii)*. There are two equilibrium outcomes; one agent follows signal and the other agent always exploits.[4] Note however that the two equilibria are not equally desirable from a social point of view. The equilibrium where the ignorant always exploits is more efficient because the probability of overexploitation is lower. Also note that if agents do not differ with respect to knowledge, case *(i)* does not exist and there is always a coordination problem.

3.2. Observable actions. When actions are observable and timing endogenous there is potentially scope for informational spillover. The timing is as follows:

1. At the beginning of the first period nature determines the state and private signals are observed. After the signals have been observed, the two agents choose between the two available actions. If both agents exploit the game ends and both receive their respective payoffs. If at least one of the agents decides not to exploit, the game continues to a second period.

[3] The probability of overexploitation is equal to $0.5(1-q_K)$ and expected payoffs for ignorant and the knowledgeable agent are equal to $0.5\left[\pi^m + q_K - (1-q_K)C\right]$ and $0.5\left[q_K - (1-q_K)C\right]$ respectively.

[4] The probability of overexploitation and expected profits are equal to those of case *(i)* if the ignorant exploits and the knowledgeable agent follows signal. If the reverse is true the probability of overexploitation is equal to $0.5(1-q_I)$ and expected payoffs for the ignorant and the knowledgeable agents are equal to $0.5\left[q_I - (1-q_I)C\right]$ and $0.5\left[\pi^m + q_I - (1-q_I)C\right]$ respectively.

2. At the second period, the agent(s) that decided not to exploit, again has (have) the two available actions to choose from. After the choice(s) has (have) been made the game ends and payoffs are realized.

We denote this game $\Gamma_o(2)$. If one of the agents exploit in the first period, the decision is based on private information only. If an agent instead decides to wait and observe the action of the other agent there is a possibility that the action will reveal some information about his signal. In such a case a better-informed decision can be made and there is a potential benefit of waiting. However, there is also a strategic cost of waiting as a consequence of the rivalry; if the resource is only large enough for one it is better to move first.[5]

PROPOSITION 2. *The obtainable equilibrium payoffs in* $\Gamma_o(2)$ *are identical to the obtainable equilibrium payoffs in* $\Gamma_u(2)$.

PROOF. See the Appendix □

The advantage of the ignorant agent is robust. Even if actions are observable and there is scope for informational spill-over, for the lower cost range, $i_K \leq C \leq i_I$, the only obtainable payoffs are that the ignorant always exploits and the knowledgeable follows signal and this is true irrespective of the sequence of actions.

4. Regulated appropriators

In this section we consider the case in which the order of moves is regulated by a public authority, who not only nominates position but also is a carrier of information (if actions are unobservable). The authority observes actions but does not have access to private information. The timing of the game is as follows.

1 At the first stage nature determines the state, both agents observe their signals and the agent assigned first position will choose whether or not to exploit.

2 At the second stage the agent assigned second position will, after having observed the action (or being informed about the action) of the first agent make her decision, after which payoffs are realized.

This game with fixed sequential ordering and observable actions is denoted $\Gamma_{reg}(2)$.[6]

[5] There could also be a direct cost of discounting but we assume it to be negligible.

[6] Note that this game could also represent the case where agents are unregulated but actions are observable and there is a natural fixed sequential order.

PROPOSITION 3. *The obtainable quilibrium payoffs in $\Gamma_{reg}(2)$ are identical to the obtainable equilibrium payoffs in $\Gamma_u(2)$ and $\Gamma_o(2)$. Moreover, if there are multiple obtainable equilibrium payoff configurations and if $k_I i_K \leq C \leq 1$, a regulator can by assigning positions choose equilibrium payoffs.*

PROOF. See the Appendix □

When appropriators are regulated there is a cost range, $k_I i_K \leq C \leq 1$, where the coordination problem can be eliminated by regulation if the ignorant is assigned first position. The intuition is that if the cost is high enough, the knowledgeable agent cannot afford to ignore the information conveyed by the action of the ignorant agent in the case where the ignorant follows signal. The only obtainable equilibrium payoff configuration is then that the ignorant always exploits and the knowledgeable follows signal. Overall welfare is maximized and the advantage of the ignorance is exacerbated.

Note that the more the agents differ with respect to knowledge, the larger is this cost range where the coordination problem can be eliminated by regulation.

5. Final remarks

The purpose of this paper was to analyze how rivals, sharing a common resource, can use their individual knowledge strategically. The main result is that having more knowledge is not necessarily better, especially if your rival has inferior knowledge. Moreover, the more the agents differ with respect to knowledge, the smaller is the probability of resource breakdown. So from a welfare perspective it is not a question of having informed or uninformed agents but rather to have heterogeneous agents

The results are obtained for agents playing pure strategies only. One could imagine situations where agents randomize. We established that there may be a coordination problem due to multiple pure strategy equilibria but did not explicitly model the cost of this. If there is no direct mechanism to overcome this coordination problem a mixed strategy equilbrium could be plausible. Consider for example an equilibrium in which both agents exploit after observing good signals and exploit with some positive probability after observing bad signals. In this case, regulation could be more valuable, as it could pick one of the pure strategy equilbria instead.

A natural extension of the model would be to let knowledge levels be endogenous by allowing agents to acquire additional knowledge at some specific cost. Depending on whether the new knowledge levels are observed by the rival, and on the cost associated with knowledge acquisition, it could be in the interest of at least one of the agents to acquire knowledge. The logic goes as follows. Consider the simultaneous move game and the equilibrium outcome where the ignorant always exploits and the knowledgeable

follows signal. It could be worthwhile for the knowledgeable to improve on informational precision in order to make a better-informed decision, because the probability of resource collapse would decrease. The knowledgeable would bear the entire cost while the ignorant would strategically remain ignorant. Note that there would be too little knowledge acquisition because the knowledgeable agent equates marginal cost of knowledge acquisition with private marginal benefit.

Appendix

Remember that

$$\begin{aligned}\Pr\left(\sigma^G \mid G,\ j\right) &= \Pr\left(\sigma^B \mid B,\ j\right) = q_j,\\ \Pr\left(\sigma^B \mid G,\ j\right) &= \Pr\left(\sigma^G \mid B,\ j\right) = (1-q_j).\end{aligned}$$

For future reference note the following; because signals are independent given state we have that

$$\Pr\left(G \mid \sigma^G,\ j\right) = \Pr\left(\sigma^G \mid G\ j\right) = q_j.$$

For simplicity and with a slight abuse of notation, from now on we will denote the bad (good) signal of an ignorant agent as σ_I^B $\left(\sigma_I^G\right)$ and similarly for the knowledgeable agent so that:

$$\begin{aligned}\Pr\left(\sigma_I^G, \sigma_K^G \mid G\right) &= \Pr\left(\sigma_I^B, \sigma_K^B \mid B\right) = q_I q_K;\\ \Pr\left(\sigma_I^B, \sigma_K^B \mid G\right) &= \Pr\left(\sigma_I^G, \sigma_K^G \mid B\right) = (1-q_I)(1-q_K);\\ \Pr\left(\sigma_I^G, \sigma_K^B \mid G\right) &= \Pr\left(\sigma_I^B, \sigma_K^G \mid B\right) = q_I(1-q_K);\\ \Pr\left(\sigma_I^B, \sigma_K^G \mid G\right) &= \Pr\left(\sigma_I^G, \sigma_K^B \mid B\right) = (1-q_I)\,q_K.\end{aligned}$$

Moreover,

$$\begin{aligned}\Pr\left(\sigma_K^G \mid \sigma_I^G\right) &= \frac{\Pr\left(\sigma_I^G, \sigma_K^G\right)}{\Pr\left(\sigma_I^G\right)} = \frac{\Pr\left(\sigma_I^G, \sigma_K^G \mid G\right)\Pr(G) + \Pr\left(\sigma_I^G, \sigma_K^G \mid B\right)\Pr(B)}{\Pr\left(\sigma_I^G \mid G\right)\Pr(G) + \Pr\left(\sigma_I^G \mid B\right)\Pr(B)}\\ &= q_I q_K + (1-q_I)(1-q_K).\end{aligned}$$

We also have that

$$\begin{aligned}\Pr\left(G \mid \sigma_I^G, \sigma_K^G\right) &= \frac{\Pr\left(G, \sigma_I^G, \sigma_K^G\right)}{\Pr\left(\sigma_I^G, \sigma_K^G\right)} = \frac{\Pr\left(\sigma_I^G, \sigma_K^G \mid G\right)\Pr(G)}{\Pr\left(\sigma_I^G, \sigma_K^G\right)}\\ &= \frac{q_I q_K}{q_I q_K + (1-q_I)(1-q_K)}.\end{aligned}$$

PROOF OF PROPOSITION 1. To prove Proposition 1 we will consider the best responses of player j to all four possible player -j strategies.

Consider first the case where player $-j$ oppose signal (exploits after observing a bad signal). In that case, the expected utility of player j of exploiting after observing a bad signal is

$$(1-q_j)(1-q_{-j}) - q_{-j}q_jC + ((1-q_j)q_{-j} + q_j(1-q_{-j}))\pi^m, \tag{A1}$$

which is positive if $i_j i_{-j} + (i_j + i_{-j})\pi^m > C$. The expected utility for player j of exploiting after observing a good signal is

$$q_j(1-q_{-j}) - q_{-j}(1-q_j)C + (q_j q_{-j} + (1-q_j)(1-q_{-j}))\pi^m, \tag{A2}$$

which is positive if $k_j i_{-j} + (k_j + i_{-j})\pi^m > C$, which always holds.

Consider next the case where player $-j$ always exploits. The expected utility for player j from exploiting after observing a good signal is given by $q_j - C(1-q_j)$, which is positive if $k_j > C$, which always holds. The expected utility for player j from exploiting after observing a bad signal is given by $(1-q_j) - Cq_j$, which is positive if $i_j > C$.

Consider next the case where player $-j$ follows signal (exploits after observing a good signal). The expected utility for player j of exploiting after observing a bad signal is given by

$$q_{-j}(1-q_j) - (1-q_{-j})q_jC + ((1-q_j)(1-q_{-j}) + q_j q_{-j})\pi^m, \tag{A3}$$

which is positive if $k_{-j}i_j + (i_j + k_{-j})\pi^m > C$, which always holds. The expected utility for player j of exploiting after observing a good signal is

$$q_{-j}q_j - (1-q_j)(1-q_{-j})C + (q_j(1-q_{-j}) + q_{-j}(1-q_j))\pi^m, \tag{A4}$$

which is greater than (A3).

Finally if player $-j$ never exploits, the best reply for player j is to exploit, because $\pi^m > 0$.

Thus, the best reply correspondence for player j is given by:

$$b_j = \begin{cases} \textit{always exploit} \text{ if player } -j \textit{ opposes signal} \text{ and } 0 < C \leq i_K i_I + (i_K + i_I)\pi^m; \\ \textit{follow signal} \text{ if player } -j \textit{ opposes signal} \text{ and } i_K i_I + (i_K + i_I)\pi^m < C \leq 1; \\ \textit{always exploit} \text{ player } -j \textit{ always exploits} \text{ and } 0 < C \leq i_j; \\ \textit{follow signal} \text{ player } -j \textit{ always exploits} \text{ and } i_j < C \leq 1; \\ \textit{always exploit} \text{ if player } -j \textit{ follows signal;} \\ \textit{always exploit} \text{ if player } -j \textit{ never exploits.} \end{cases} \tag{A5}$$

Because it is never a best response to *oppose signal* or to *never exploit* we can eliminate these strategies for player $-j$ and the relevant best reply correspondence for player j is thus given by;

$$b_j = \begin{cases} \textit{always exploit} \text{ if player } -j \textit{ always exploits} \text{ and } 0 < C \leq i_j; \\ \textit{follow signal} \text{ if player } -j \textit{ always exploits} \text{ and } i_j < C \leq 1; \\ \textit{always exploit} \text{ if player } -j \textit{ follows signal.} \end{cases} \tag{A6}$$

□

PROOF OF PROPOSITION 2. The set of feasible outcomes is;

(A7)
(i) the knowledgeable always exploits, the ignorant always exploits
(ii) the knowledgeable always exploits, the ignorant follows signal
(iii) the knowlegeable always exploits, the ignorant never exploits
(iv) the knowledgeable follows signal, the ignorant always exploits
(v) the knowlegeable follows signal, the ignorant follows signal
(vi) the knowledgeable follows signal, the ignorant never exploits
(vii) the knowledgeable never exploits, the ignorant always exploits
(viii) the knowledgeable never exploits, the ignorant follows signal
(ix) the knowledgeable never exploits, the ignorant never exploits.

We first show that the payoffs associated with case (i), (iii), (v), (vi), (vii), (viii) and (ix) cannot be obtained in a pure PBE outcome. To verify that case (ix), (vi) and (viii) cannot be sustained in a pure PBE outcome note that if the opposing agent, agent $-j$, never exploits it is always a strict best reply to always exploit because $\pi^m > 0$. Morover, we can eliminate cases (i), (iii), (vii). These are payoff configurations where an agent's decision problem is identical in both time periods beacuse actions does not carry information. This means that we can rely on the proof of Proposition 1 and conclude that these configurations cannot be sustained in a pure PBE outcome. We can also exclude case (v) for both cost ranges. Consider the case where the knowledgeable follows signal. If both agents take their actions at the first period or both at the second period once again we can rely on the proof of Proposition 1. If the knowledgeable take the decision in the first period and the ignorant in the second, the ignorant will exploit at the second period beacuse the expected utlity from doing so after observing a good signal,

$$q_I q_K - (1 - q_I)(1 - q_K) C, \tag{A8}$$

and the expected utility after observing a bad signal,

$$(1 - q_I) q_K - q_I (1 - q_K) C, \tag{A9}$$

are both strictly positive. If the knowledgeable agent take her decision in the second period and the ignorant at the first period, again actions do not carry information and we can conclude that case (v) cannot be sustained for any cost range. It remains to consider cases (ii) and (iv).

We now check that the payoff configuration of case (ii) cannot be obtained for the cost range $i_I \leq C \leq 1$. If the knowledgeable always exploits, the decision problem for the ignorant is the same in both time periods. The ignorant will exploit (either in the first or in the second period) after observing a bad signal as long as expected profit is positive, i.e if

$$(1 - q_I) - q_I C > 0, \tag{A10}$$

which is true only if $C < i_I$.

We next check that the payoff configuration of case (ii) can be obtained in a pure PBE outcome for the cost range $i_I \leq C \leq 1$. Consider the following belief of the ignorant; {first period: the knowledgeable agent always exploits, second period: if the knowledgeable did not exploit in the first period she always exploits} and the following belief of the knowledgeable; {first period: the ignorant follows signal, second period: if the knowledgeable did not exploit in the first period the ignorant always exploits, if the knowledgeable exploited in the first period the ignorant will follow signal}.

Given this belief it is a best response for the knowledgeable agent to exploit in the first period because the expected payoff from exploiting in the first period after observing a bad signal is given by

$$q_I (1 - q_K) - (1 - q_I) q_K C + ((1 - q_K)(1 - q_I) + q_K q_I) \pi^m > 0, \tag{A11}$$

and if the game continues to a second period, it is given by (A11) if the ignorant followed signal in the first period; and if the ignorant did not follow signal in the first period it is given by $(1 - q_K) - q_K C < 0$. After observing a good signal the expected utility from exploiting in the first period is given by

$$q_I q_K - (1 - q_K)(1 - q_I) C + (q_K (1 - q_I) + q_I (1 - q_K)) \pi^m, \tag{A12}$$

and if the game continues to a second period, it is given by (A12) if the ignorant followed signal in the first period; and if the ignorant did not follow signal it is given by $q_K - (1 - q_K) C$, which is less than (A12). So it is a best response for the knowledgeable to exploit in the first period.

For the ignorant agent it is a best response to follow signal in the first period. The expected utility from exploiting in the first period is equal to the expected utility from exploting in the second period which is given by $q_I - (1 - q_I) C > 0$, if the agent observes

a good signal. If the agent observes a bad signal it is given by $(1-q_I)-q_IC<0$. Thus, the outcome {the knowledgeable always exploits in the first period, the ignorant follows signal in the first period} can be sustained as a pure PBE outcome of the game.

Finally we show that the payoff configuration of case (iv) can be obtained in a pure PBE outcome for all cost ranges.

Consider the following belief of the ignorant; {first period: the knowledgeable follows signal, second period: the knowledgeable always exploits if the ignorant did not exploit in the first period and follows signal if the ignorant exploited in the first period} and the following belief of the knowledgeable {first period: the ignorant always exploits, second period: the ignorant always exploits}

Given this belief it is a best response for the ignorant to exploit in the first period because the expected payoff from exploiting in the first period after observing a bad signal is given by

$$q_K(1-q_I)-(1-q_K)q_IC+((1-q_I)(1-q_K)+q_Iq_K)\pi^m>0, \tag{A13}$$

and if the game continues to a second period it is given by (A13) if the knowledgeable followed signal in the first period; and if the knowledgeable did not follow signal in the first period it is given by $(1-q_I)-q_IC$, which is less than (A13). After observing a good signal, the ignorant's expected utility from exploiting in the first period is given by

$$q_Kq_I-(1-q_I)(1-q_K)C+(q_I(1-q_K)+q_K(1-q_I))\pi^m, \tag{A14}$$

and if the game continues to a second period is given by (A14) if the knowledgeable followed signal in the first period and if the knowledgeable did not follow signal, it is given by $q_I-(1-q_I)C$, which is less than (A14). So it is a best response to exploit in the first period.

For the knowledgeable agent, it is a best response to follow signal in the first period. The expected utility from exploiting in the first period is equal to the expected utility from exploting in the second period and this is given by $q_K-(1-q_K)C>0$ if the agent observes a good signal. If the agent is observing a bad signal it given by $(1-q_K)-q_KC<0$. Thus the outcome {the knowledgeable follows signal in the first period, the ignorant exploits in the first period} can be sustained as a pure PBE outcome of the game. □

PROOF OF PROPOSITION 3. The technique used in this proof is similar to that in the proof of Proposition 1 and 2 so we will omit some calculations. Consider again the potential payoff configurations given by (A7) in the proof of Proposition 2.

Note first that case (i), (iii), (v), (vi), (vii), (viii) and (ix) cannot be obtained and that case (ii) cannot be obtained for the cost range $i_K \leq C \leq i_I$. These payoff configurations can be dismissed by the same argments as in the proof of Proposition 2.

Next note that case (ii) cannot be obtained for the cost range $k_I i_K \leq C \leq 1$ unless the knowledgeable is assigned first mover. Consider first the case where the knowledgeable moves first and the ignorant holds the belief {the knowledgeable always exploits} and the knowledgeable holds the belief {the ignorant follows signal}. At the second period if the knowledgeable exploits, it is a best response for the ignorant to follow signal beacuse $C \geq i_I$. If the knowledgeable does not exploit, the best response is to exploit because $\pi^m > 0$. At the first period, given that the ignorant follows signal, the best response for the knowledegable is to exploit if observing a bad signal because the expected utility given by (A11) is positive and the expected utility from exploiting after observing a bad signal given by (A12) which is greater than (A11).

Consider next the case where the knowledgeable is assigned the second move. At the second period, given that the ignorant follows signal, and has exploited, the best response for the knowledgeable after observing a bad signal is not to exploit, because the expected utility is

$$q_I (1 - q_K) - (1 - q_I) q_K C < 0. \tag{A15}$$

Note next that case (ii) can be obtained in a pure PBE for the cost range $i_I \leq C \leq k_I i_K$ irrespective of ordering. This is easy to verify considering that (A15) is positive for this range of values.

Finally we can note that case (iv) can be obtained in a pure PBE outcome for the entire cost range. Consider for example the case where the knowledgeable moves first and the belief of the ignorant is {the kowledgeable follows signal} and the belief of the knowledgeable is {the ignorant always exploits}. Given this pair of beliefs, the best response is for the ignorant to exploit because the expected utility from exploiting after observing a good signal is (A8) and after observing a bad signal is given by (A9) and both are positive. It is a best response for the knowledgeable to follow signal because the expected utility after exploiting, given by $(1 - q_K) - q_K C$, is negative for the entire cost range. □

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PAPER 3

Grazing Games

Anne-Sophie Crépin and Therese Lindahl

III

ABSTRACT. Grasslands used for domestic livestock are often the common property of several owners and are typically characterized by complex ecosystem dynamics. When grass is taken as a fixed production factor we verify the standard result that non-cooperative farmers keep higher stock of cattle and have higher grazing pressure than cooperative farmers. However, when we account for grassland dynamics the picture becomes more complex and the conventional result may not necessarily hold.

1. Introduction

Grasslands cover about 40 percent of the surface of the earth and are found in every region of the world — excluding Greenland and Antarctica. Many grasslands are used for domestic livestock and as livestock densities have increased, many grasslands has degraded. Today, no less than 50 percent of the grasslands are degraded, mainly due to overgrazing. (White, Murray and Rohweden, 2000).

Such resource degradation is traditionally imputed to ill-defined property rights. Grasslands are often the common property of several farmers. The group can exclude any outsider but amongst themselves, the users are rivals. Such a setup typically results in suboptimal use.

Most of the standard models of Common Pool Resources (CPR's) assume that the resource shared is of fixed size or can generate a constant flow of services. However, many natural resources, including grasslands, evolve over time and adapt to changes in the wider environment, often in a non-linear fashion. Previous research shows that it is very challenging, also for a social planner, to manage such convex-concave resources because the non-linear dynamics can make the ecosystem flip between alternate stable states and even marginal changes can cause radical transformations of the ecosystem.[1]

[0] We are very grateful to Karl-Göran Mäler for many valuable comments. We also want to thank Jon Norberg, Tore Ellingsen and Jörgen Weibull for contributing discussions on the topic. This paper also benefited from seminar discussions at the 11th Ulvön Conference on Environmental Economics, at the 14th EAERE Conference in Budapest and at Stockholm School of Economics.

[1] See, for example, the seminal paper by Ludwig, Jones and Holling (1978) and the papers by Crépin (2002), Brock and Starrett (2003), Crépin (2003), and Mäler, Xepapadeas and de Zeeuw (2003).

There is evidence that above some critical value of grazing pressure, grasslands can flip from a grass-dominated state to an alternate state that is either woody plants-dominated or a dry desert (Resilience Alliance 2005). The already existing ecological models of grasslands (see, for example, Janssen Anderies and Walker 2004, Perrings and Walker 1997) fail to capture the rivalry between resource users, thus ignoring the economics of the problem.

The purpose of this paper is to combine economic factors with ecological characteristics to provide a more complete picture of the overgrazing problem.

To capture ecosystem complexity together with the institutional structure, we model the problem as a differential game (Dockner et al. 2002) where each farmer maximizes profits, given the dynamics of cattle and grass interaction and given the existence of multiple users. We compare the outcome for cooperative farmers – acting like a sole owner – with that for non-cooperative farmers. Farmers do not derive any other benefits from the grassland except those associated with grazing.[2]

Note that, although these results are obtained for farmers sharing a common grassland, they could be generalized to other types of ecosystems, where the resource is characterized by convex-concave dynamics. According to recent findings, that description fits many resources today. (Steffen et. al 2004)

If grass is taken as a fixed production factor, we verify the standard result that non-cooperative farmers keep higher stock sizes and have higher grazing pressure than cooperative farmers. Moreover, impatient farmers exploit the grassland less than patient farmers. This may seem counterintuitive but, in fact, it is not for the control variable, animal off-take, has an indirect effect on grass biomass. Impatient farmers harvest their stocks at the beginning of the time span, thereby preventing future cattle growth which means that they sustain smaller steady-state stock sizes and thus less grazing pressure.

When accounting for grassland dynamics, the picture becomes more complex. A higher discount rate also decreases the value of future grass biomass, inducing farmers to, on average, keep higher stocks of cattle and grazing pressure. The total effect of the discount rate depends on the characteristics of the grassland. In particular we show that the two management regimes may respond differently (both in magnitude and direction) to a change in the discount rate, which means that the conventional result does not necessarily hold.

This paper is perhaps closest in its approach to the article by Mäler, Xepapadeas and de Zeeuw (2003) on the economics of shallow lakes that can flip between a clear and

[2] In reality, grasslands may produce other services such as coal storage, biodiversity, tourism and recreation.

a dirty turbid state. By choosing relative weights and given that the discount rate is sufficiently low, Mäler et al. show that it is optimal to manage the lake in a clear state. When there are several communities, there might be a situation where the lake flips to the eutrophic state. Their control variable has a direct effect on the resource[3], whereas our control variable – the animal off-take – only indirectly affects grass biomass through the change in cattle stock. Moreover, our farmers maximize profits, which means that even though the cooperative solution internalizes the externality, it may not necessarily be the social optimum.

The paper is organized as follows. Section 2 presents the ecological model and the economics of grazing. In section 3, we combine these elements and analyze different models of strategic interaction between grassland users. In section 3.1, the users cooperate, whereas they do not in the following section where they use open loop strategies. Section 3.3 discusses Markovian strategies and Section 4 concludes.

2. The model

2.1. Grassland dynamics. We consider n identical farmers, who together have exclusive access to a piece of grassland where they let their cattle graze. Let $S_i(t)$ represent farmer i's private cattle stock at time t. The total stock of cattle on the land at time t is $S = \sum_{i \in I} S_i$, where $I \equiv \{1, 2, ..., n\}$. Let R, D and K denote, respectively, the cattle's intrinsic growth rate, the rate of competition between cattle and the land's carrying capacity for cattle. Land scarcity, the size of the other farmers' stock and the animal off-take (harvest) H_i that farmer i makes on her stock prevents cattle growth. With a logistic cattle growth[4], equation (2.1) gives the equation of motion for farmer i's stock of cattle

$$\frac{dS_i}{dt} = RS_i\left(1 - D\frac{S}{K}\right) - H_i. \tag{2.1}$$

If $H = \sum_{i \in I} H_i$, the equation of motion for the total cattle stock is:

$$\frac{dS}{dt} = RS\left(1 - D\frac{S}{K}\right) - H. \tag{2.2}$$

This logistic equation for cattle growth ignores the fact that cattle and grass are part of a complex dynamic ecosystem where grass and cattle interact; grass biomass

[3] The control variable is the loads of nutrients directly affecting the lake dynamics.

[4] The logistic model proposed by Verhulst (1838) was originally meant to represent human population growth, but has since then been also shown to be applicable to numerous other populations.

affects grazing and thereby also cattle growth[5] and grazing affects grass biomass. There is evidence of grazing being typically non-linear[6]; for low grass biomass, cattle spend most of their time searching for grass, for high grass biomass, cattle spend most of their time ingesting it. We find the highest grazing pressure for intermediate grass biomasses. Put differently, when grass biomass is below some critical value, X — the so-called half saturation grass biomass — grazing pressure is convex and for grass biomasses above this critical value, grazing pressure is still increasing in grass biomass, but is now concave. We let the term (2.3) capture such grazing pressure, i.e. the amount of grass that cattle eat[7]

$$BS\frac{G^2}{X^2+G^2}. \tag{2.3}$$

Cattle growth is then given by:

$$\frac{dS}{dt} = \varepsilon BS\frac{G^2}{X^2+G^2}\left(1 - D\frac{S}{K}\right) - H. \tag{2.4}$$

Parameter ε represents the share of eaten grass that cattle can assimilate as growth. In equation (2.4), grass biomass is still constant but this is only part of the story because grazing also affects grass growth. Grazing decreases grassland resilience and above some critical grazing pressure, the grassland may undergo a sudden change, a so-called flip — the grassland goes from being grass-dominated to woody-plants dominated, or may become a desert.[8]

Let U be the crown biomass and UA the ability to sprout new shoots, known as the tiller potential. Let C be the land's carrying capacity for grass. Equation (2.5) summarizes grassland dynamics, where the first part describes grass growth in a grassland where cattle is absent and the second part describes the effect of grazing[9]

$$\frac{dG}{dt} = U(A+G)\left(1 - \frac{G}{C}\right) - BS\frac{G^2}{X^2+G^2}. \tag{2.5}$$

[5] Grass biomass could affect cattle growth via the growth rate or the carrying capacity.

[6] See the threshold database of the Resilience Alliance, 2005.

[7] This sigmoid functional form is often referred to as a Holling-type predation term (Holling, 1959) and has been shown to be useful in modelling ecosystems with multiple stable states and threshold effects.

[8] Scholes and Archer (1997), Anderies, Janssen and Walker (2002), and Scholes (2003) have modelled such systems in different ways. Here, we use a simplified version of the model presented in Janssen, Anderies and Walker (2004).

[9] We abstract from wild animals' grazing.

Resilience is here referred to as the ecosystem's capacity to tolerate disturbances without collapsing into an alternate state. A high regrowth potential A, and a high half saturation point, X capture this notion. For a given grass biomass, the higher the values of these parameters, the higher the steady-state stock that can be sustained by the grassland – the higher the resilience.

To simplify the analysis, we transform this system into a dimensionless system with similar dynamics (Segel 1972). Let u_S, u_G and u_t be cattle, grass and time measurement units so that $s = \frac{S}{u_S}$, $h = \frac{Hu_t}{u_S}$, $g = \frac{G}{u_G}$, and $\tau = \frac{t}{u_t}$ represent dimensionless variables of cattle, harvest grass biomass and time, respectively. Then, we choose measurement units so that $u_g = C$, $u_s = \frac{CU}{B}$, $u_t = \frac{1}{U}$, and define the new parameters $b = \frac{\varepsilon B}{U}$, $x = \frac{X}{C}$, $a = \frac{A}{C}$ and $k = \frac{BK}{DCU}$. This yields the system (2.6)[10]

$$\dot{s} = bs\frac{g^2}{x^2+g^2}\left(1-\frac{s}{k}\right) - h \tag{2.6a}$$

$$\dot{g} = (a+g)(1-g) - s\frac{g^2}{x^2+g^2}. \tag{2.6b}$$

Farmers determine the size of their own stock, and thereby also indirectly the effect on grass dynamics through their choice of animal off-take. For now, we consider a constant harvest and focus on grass–cattle interaction and the role of the threshold. The system's dynamics (2.6) are best illustrated in a phase diagram where $S_\phi(g)$ and $S_\varphi(g)$, respectively, show combinations of cattle and grass, such that the graphs of cattle and grass stock, respectively, are invariant[11]

$$S_\phi(g) = \frac{k}{2}\left(1 \pm \sqrt{1 - \frac{4h}{bk}\frac{x^2+g^2}{g^2}}\right) \tag{2.7a}$$

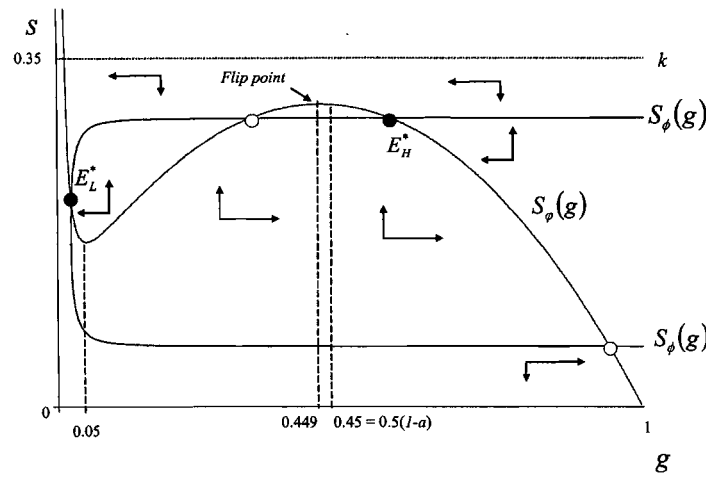
$$S_\varphi(g) = (a+g)(1-g)\left(\frac{x^2+g^2}{g^2}\right). \tag{2.7b}$$

If grazing has a linear effect, $x = 0$, $S_\varphi(g)$ is strictly concave. If grazing has a non-linear effect ($x > 0$) and the resilience is relatively high (high a and high x), $S_\varphi(g)$ is strictly convex. In both cases, the system only has one stable steady state. A third, more interesting case, on which we focus, occurs when grazing is non-linear and resilience is relatively low, for then $S_\varphi(g)$ is convex-concave. This reflects a situation where the grassland may flip between alternate stable states.

Figure 1 depicts a situation with four steady states, situated at the intersection of both curves. The arrows indicating the system dynamics show that we only find stable

[10] The exact derivation can be found in the Appendix.

[11] The motivation behind the phase diagram can be found in the Appendix.



$a = 0.1, x = 0.02, k = 0.35, b = 0.2, h = 0.01$

FIGURE 1. Phase diagram of the cattle-grass ecosystem

steady states where $S_\varphi(g)$ is decreasing and $S_\varphi(g)$ is increasing $\left(S_\varphi^+(g)\right)$ in grass biomass. The state denoted E_H^* represents a stable state with high grass biomass, whereas E_L^* represents a stable state with low grass biomass. For the harvest level chosen, initial grass biomass determines in which of the stable states the ecosystem will end up.

To get an understanding of the flipping mechanism, imagine us to be in a high grass biomass stable state and that for some reason, the harvest level decreases (grazing pressure increases). The curve $S_\varphi^+(g)$ shifts upwards. If the change in grazing pressure is high, the ecosystem cannot cope with this change and the grassland flips to a low grass biomass steady state.

In the remainder of this article, farmers control animal off-take. Note that this control variable does not directly enter the equation for grass growth, so that the properties of the grass-cattle relationship given by $S_\varphi(g)$ will also hold in the following sections.

2.2. The static case. In this section, we adopt the standard economic approach, treating grass as a fixed production factor. This enables us to focus on the rivalry between farmers and the economics of grazing. We let each farmer $i \in I \equiv \{1, 2, ..., n\}$, choose animal off-take to maximize profits and sell the off-take at a constant price p. The cost for holding cattle is additively separable, convex in off-take and linear in stock size[12]; $c(s_i, h_i) = c_1(h_i) + c_2 s_i$, where $c_1' = \frac{dc_1}{dh_i} > 0$ and $c_1'' = \frac{d^2 c_1}{dh_i^2} > 0$. The profit from holding cattle is then:

$$\pi(h_i, s_i) = p_i h_i - c_1(h_i) - c_2 s_i. \tag{2.8}$$

Consider a static game between identical farmers. Grass biomass and cattle are constant, but there is still rivalry between the farmers. There are several ways of modeling rivalry but, for the sake of comparison, we let equation (2.6a) (from the previous section) in steady state capture this rivalry.

$$b s_i \frac{g^2}{x^2 + g^2}\left(1 - \frac{n s_i}{k}\right) - h_i = 0. \tag{2.9}$$

Cooperative farmers choose harvest to maximize total profits, given the condition on rivalry, whereas non-cooperative farmers choose harvest to maximize their own profits, given the condition on rivalry, and given the others farmers' choices of stock size, where $\sum_{j \neq i} s_j = \Psi^{-i}$. This results in two different problems

(Cooperation)
$$\max_{h_i} n\left(p h_i - c_1(h_i) - c_2 s_i\right)$$
$$\text{s.t.: } n s_i b \frac{g^2}{x^2 + g^2}\left(1 - \frac{n s_i}{k}\right) - n h_i = 0$$

(Non-cooperation)
$$\max_{h_i} \left(p h_i - c_1(h_i) - c_2 s_i\right)$$
$$\text{s.t.: } s_i b \frac{g^2}{x^2 + g^2}\left(1 - \frac{s_i + \Psi^{-i}}{k}\right) - h_i = 0.$$

The total equilibrium stocks in cooperation and non-cooperation are then s^{co*} and s^{no*}, respectively

[12] The cost of holding cattle is linear, or at least piecewise linear. The assumption of convexity of the harvest cost is crucial for ensuring an interior solution, but this is not true for the cost of holding cattle. However, assuming linearity definitely simplifies the derivations and presentations of the results.

$$s^{co*} = \frac{1}{2}k\left(1 - \frac{x^2+g^2}{g^2}\frac{c_2}{(p - c_1'(h_i))}\right) \tag{2.10}$$

$$s^{no*} = \frac{n}{(n+1)}k\left(1 - \frac{x^2+g^2}{g^2}\frac{c_2}{(p - c_1'(h_i))}\right). \tag{2.11}$$

In the Appendix, we show that $s^{no*} > s^{co*}$.

REMARK 1. *If grass is taken as a fixed production factor, we confirm the conventional result that non-cooperation is associated with suboptimal use; total stock size and grazing pressure will be larger than the efficient level.*

Non-cooperative farmers would benefit from sizing down their stocks but they will not, because each farmer realizes that if she decreases her stock she will share the associated benefits with the other farmers but bear the entire cost herself. This standard CPR explanation[13] to grassland degradation does not account for resource dynamics. To draw a more complete picture of grazing problems, let us combine rivalry and grassland dynamics.

3. Grass dynamics and the economics of harvest

3.1. Cooperation. Consider once more n symmetrical farmers choosing harvest levels to maximize the sum of their discounted joint profit, given the dynamic interaction between cattle and grass. Their problem is stated below

$$\max_{h_1,h_2,\ldots,h_n} \int_0^{+\infty}\left(ph - \sum_{i\in I} c_1(h_i) - c_2 s\right)e^{-\rho t}dt \tag{3.1}$$

$$s.t:$$

$$\forall i \in I, \dot{s}_i = bs_i\frac{g^2}{x^2+g^2}\left(1 - \frac{s}{k}\right) - h_i \tag{3.2}$$

$$\dot{g} = (a+g)(1-g) - s\frac{g^2}{x^2+g^2}. \tag{3.3}$$

We use Pontryagin's principle (1964) to solve this dynamic problem. Let $\lambda = (\lambda_i)_{i\in I}$ and μ denote the shadow prices for cattle and grass, respectively. $\mathcal{H}(s_i, g, h_i, \lambda_i, \mu)$ denotes the Hamiltonian

[13] In his classical essay, *The Tragedy of the Commons* (1968), Hardin's example was in fact a number of herdsmen sharing a common pasture land.

$$\begin{aligned}(3.4)\qquad \mathcal{H}(s_i, g, h_i, \lambda_i, \mu) &= ph - \sum_{i\in I} c_1(h_i) - c_2 s \\ &+ \sum_{i\in I} \lambda_i \left(s_i b \frac{g^2}{x^2+g^2}\left(1-\frac{s}{k}\right) - h_i \right) \\ &+ \mu \left((a+g)(1-g) - s\frac{g^2}{x^2+g^2} \right).\end{aligned}$$

Equations (3.5), (3.6) and (3.7) give the first-order necessary conditions for a maximum[14]

$$(3.5)\qquad p - c_1'(h_i) - \lambda_i = 0,$$

$$(3.6)\qquad \dot{\lambda}_i = \lambda_i \left(\rho - \frac{g^2}{x^2+g^2} b \left(1 - \frac{2s}{k}\right)\right) + c_2 + \mu \frac{g^2}{x^2+g^2}$$

$$(3.7)\qquad \dot{\mu} = \mu \left(\rho - 1 + 2g + a + s\frac{2gx^2}{(x^2+g^2)^2}\right) - \lambda_i s b \left(1 - \frac{s}{k}\right) \frac{2gx^2}{(x^2+g^2)^2}.$$

Because farmers are symmetric and the cost function of harvest is strictly convex, i.e. the marginal cost is invertible, we have a unique interior solution (equation 3.5 holds with equality) which says that the optimal level of harvest for each farmer is such that the marginal benefit of harvest, p, equals the marginal cost of harvest, which is the "direct" marginal cost of harvest, $c_1'(h_i)$, plus the marginal value of the cattle if they remain in the ecosystem, λ_i.[15] We have n differential equations for the shadow value of stocks, $\dot{\lambda}_i$, but due to symmetry, they are all identical. Equation (3.5) gives $\dot{\lambda}_i = -c_1''(h_i)\dot{h}_i$ and can be used together with (3.6) to obtain an equation of motion for animal off-take for farmer i

$$(3.8)\qquad \dot{h}_i = \frac{1}{c_1''(h_i)} \left((p - c_1'(h_i)) \left(b\frac{g^2}{x^2+g^2}\left(1-\frac{2s}{k}\right) - \rho \right) - c_2 - \mu\frac{g^2}{x^2+g^2} \right).$$

Consider first the dynamic case where we ignore grassland dynamics ($\mu = 0$). Then, the relation (3.8) shows that the rate of animal off-take increases if the net marginal cost of holding cattle, c_2, decreases, the net marginal value of cattle productivity, $(p - c_1'(h_i))\, b\frac{g^2}{x^2+g^2}\left(1 - \frac{2s}{k}\right)$, increases and if cattle's saturation point, x decreases. These factors increase farmers' stock sizes (and grazing pressure), which enables them to harvest more in later periods. If farmers are impatient, they harvest more in earlier

[14] In the Appendix, we also present the concavity conditions required for sufficiency.

[15] The unique solution is given by $h_i^* = (c_1')^{-1}(p - \lambda_i)$. Optimal harvest is monotonously increasing in p and monotonously decreasing in λ_i.

periods (lower grazing pressure), thereby preventing future cattle growth which means that the harvest rate decreases with time.

If farmers account for grass dynamics and provided that $\mu > 0$, farmers keep higher harvest levels at the beginning (lower grazing pressure), which means that they harvest less in later periods. We use equation (3.8) to solve for the steady-state total stock of cattle

$$ns_i^{co*} = \frac{k}{2}\left(1 - \frac{c_2}{(p - c_1'(h_i))}\frac{x^2+g^2}{bg^2} - \rho\frac{x^2+g^2}{bg^2} - \frac{\mu}{(p - c_1'(h_i))}\right). \tag{3.9}$$

If we ignore grassland dynamics ($\mu = 0$), this stock equation is comparable to the cooperative cattle stock in the static case, the only difference being the term $\rho\frac{x^2+g^2}{bg^2}$, which represents the need to restrict the stock to ensure higher future profits. The direct effect of grass dynamics is given by the relative shadow value of grass. Using equation (3.7) and (3.3) in steady state, we can solve for the relative shadow value of grass in steady state

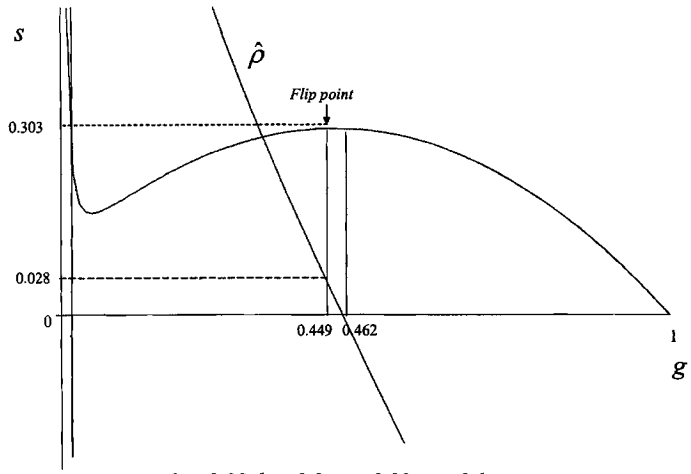
$$\frac{\mu}{(p - c_1'(h_i))} = \frac{(kg^2 - (a+g)(1-g)(x^2+g^2))\,2x^2(a+g)(1-g)}{bkg^2(g(\rho - 1 + 2g + a)(x^2+g^2) + (a+g)(1-g)\,2x^2)}. \tag{3.10}$$

Some properties of the shadow value of grass are summarized in Lemma 1.

LEMMA 1. *For cooperative farmers in steady state;*
i) the shadow value of grass is positive, $\mu > 0$,
ii) the effect of grass dynamics is larger for patient farmers, $\frac{\partial\mu}{\partial\rho} < 0$.

PROOF. See the Appendix □

From equation (3.9) and Lemma 1, we see that the discount rate influences the steady-state stock in two ways. A higher discount rate decreases the value of future profits, thus inducing farmers to harvest more in early time periods (keeping a lower stock and grazing pressure), preventing future cattle growth, which means that the steady-state stock and grazing pressure are lower. We can note two features of this effect. First, the effect also holds if grass is considered a fixed production factor and, second, it is the result of the indirect control of the resource. A higher discount rate also decreases the value of future grass biomass, inducing farmers to, on average, keep higher stocks of cattle and grazing pressure. The total effect of the discount rate depends on the characteristics of the grassland and grass biomass.



$k = 0.35,\ b = 0.2,\ x = 0.02,\ a = 0.1$

FIGURE 2. Critical discount rate

PROPOSITION 1. *There exists a critical value $\hat{\rho}(k, a, x, g)$ of the discount rate above which the steady state cattle stock decreases in the discount rate and below which the opposite holds; $\rho > \hat{\rho}(k, a, x, g) \Leftrightarrow \frac{\partial s^{*co}}{\partial \rho} < 0$. The critical discount rate is given by*

$$\hat{\rho}(., g) = 1 - 2g - a - \left(\frac{2(a+g)(1-g)x^2}{g(x^2+g^2)} - \frac{\sqrt{\frac{(kg^2-(a+g)(1-g)(x^2+g^2))2x^2(a+g)(1-g)}{k}}}{g(x^2+g^2)} \right).$$

PROOF. See the Appendix. □

Suppose the ecosystem to be in a grass dominated state and the grass biomass to be high/moderate (in Figure 2, grass biomass is higher than 0.462). For this grass biomass, grazing only has a moderate effect on grass biomass. The critical discount rate, $\hat{\rho}(k, a, x, g)$, is negative, which implies that the cattle effect dominates. The more impatient are the farmers, the lower is the steady-state cattle stock and grazing pressure. However, for intermediate grass biomasses, (in Figure 2 grass biomass is between 0.449 and 0.462), grazing has a large effect. If farmers are sufficiently patient, $\rho < \hat{\rho}(k, a, x, g)$, the grass effect dominates and steady-state stock is increasing in the discount rate. If farmers are patient they keep higher stocks of cattle and grazing

pressure at the beginning of the time span. Grazing has a large effect, and the grassland can only sustain a smaller steady-state stock of cattle.

3.2. Open loop. Consider now a situation where the farmers do not cooperate. Each farmer decides at the very beginning of the time span how to behave and commit to this strategy. In an open loop Nash equilibrium, each profit function is maximized separately, given the dynamic constraint of the grassland and the farmers' expectations about the grazing path of the other farmers. We let $\Psi^{-i} = \sum_{j \neq i} s_j$. Each farmer faces the problem:

$$\max_{h_i} \int_0^{+\infty} \left(ph_i - c_1(h_i) - c_2 s_i\right) e^{-\rho t} dt \tag{3.11}$$

$$s.t.:$$

$$\dot{s}_i = s_i b \frac{g^2}{x^2 + g^2}\left(1 - \frac{s_i + \Psi^{-i}}{k}\right) - h_i \tag{3.12}$$

$$\dot{g} = (a+g)(1-g) - \left(s_i + \Psi^{-i}\right)\frac{g^2}{x^2+g^2}. \tag{3.13}$$

Let $\lambda^{ol} \equiv (\lambda_i^{ol})_{i \in I}$ and μ^{ol} denote the respective shadow prices for cattle and grass, when farmers use open loop strategies. The Hamiltonian for this problem:

$$\begin{aligned} \mathcal{H}\left(s_i, h_i, g, \lambda_i^{ol}, \mu^{ol}\right) &= ph_i - c_1(h_i) - c_2 s_i \\ &+\lambda_i^{ol}\left(s_i b \frac{g^2}{x^2+g^2}\left(1 - \frac{s_i + \Psi^{-i}}{k}\right) - h_i\right) \\ &+\mu^{ol}\left((a+g)(1-g) - \left(s_i + \Psi^{-i}\right)\frac{g^2}{x^2+g^2}\right). \end{aligned} \tag{3.14}$$

Applying the same technique used for the cooperative case, we once more obtain an equation of motion for harvest

$$\dot{h}_i = \frac{1}{c_1''(h_i)}\left((p - c_1'(h_i))\left(b\frac{g^2}{x^2+g^2}\left(1 - \frac{(n+1)s_i}{k}\right) - \rho\right) - c_2 - \mu^{ol}\frac{g^2}{(x^2+g^2)}\right). \tag{3.15}$$

Comparing this equation with the associated equation for the cooperative case (equation 3.8), we can note that they are of identical form. However, farmers using open loop strategies do not consider the competitive effect of their stock on the other farmers' stock, which will induce them to keep higher stocks and grazing pressure. This is the conventional inefficiency associated with non-cooperation (as discussed in section

2.2). Moreover, the shadow price for grass differs, $\mu^{ol} \neq \mu$. Consider first the case when $\mu^{ol} < \mu$, non-cooperative farmers assign a lower future grass biomass and consequently, keep even higher stocks, higher grazing pressure and a higher rate of harvest. On the other hand, if $\mu^{ol} > \mu$, non-cooperative farmers keep lower stocks and lower grazing pressure, and the total effect is ambiguous. From equation (3.15), we can solve for steady-state cattle stock

$$ns_i^{ol*} = \frac{n}{n+1}k\left(1 - \frac{c_2}{(p - c_1'(h_i))}\frac{x^2+g^2}{bg^2} - \rho\frac{x^2+g^2}{bg^2} - \frac{\mu^{ol}}{(p - c_1'(h_i))}\right) \tag{3.16}$$

and

$$\frac{\mu^{ol}}{(p - c_1'(h_i))} = \frac{(kg^2 - (a+g)(1-g)(x^2+g^2))\,2x^2(a+g)(1-g)}{nbkg^2(g(\rho - 1 + 2g + a)(x^2+g^2) + (a+g)(1-g)2x^2)}. \tag{3.17}$$

LEMMA 2. *For non-cooperative farmers using open loop strategies in steady state;*
i) the shadow value of grass is positive, $\mu^{ol} > 0$
ii) the effect of grass dynamics is larger for patient farmers, $\frac{\partial \mu^{ol}}{\partial \rho} < 0$.

PROOF. See the Appendix □

PROPOSITION 2. *For a given grass biomass, the relative shadow value for grass in steady state is lower for farmers using open loop strategies, $\mu^{ol} = \frac{\mu}{n}$, which implies that the corresponding critical discount rate is lower for farmers using open loop strategies, $\hat{\rho}^{ol}(k,a,x,g) < \hat{\rho}(k,a,x,g)$ where*

$$\hat{\rho}^{ol}(.,g) = 1 - 2g - a - \left(\frac{2(a+g)(1-g)x^2}{g(x^2+g^2)} - \frac{\sqrt{\frac{(kg^2-(a+g)(1-g)(x^2+g^2))2x^2(a+g)(1-g)}{nk}}}{g(x^2+g^2)}\right).$$

PROOF. See the Appendix. □

Proposition 2 has some implications. In particular, consider the case where grass biomass is intermediate (in Figure 3 between 0.449 and 0.462) and farmers are patient, such that $\hat{\rho}^{ol}(k,a,x,g) < \rho < \hat{\rho}(k,a,x,g)$. Imagine that the discount rate increases. A higher discount rate decreases the value of future grass biomass, inducing farmers to, on average, keep higher stocks of cattle and grazing pressure. However, a higher discount rate also decreases the value of future profits, inducing farmers to harvest more in early time periods, i.e. to reduce their stocks in the beginning of the time span.

When non-cooperative farmers decrease their stock sizes they do not consider the competitive effect of their stock on other farmers' stocks, which means they do not

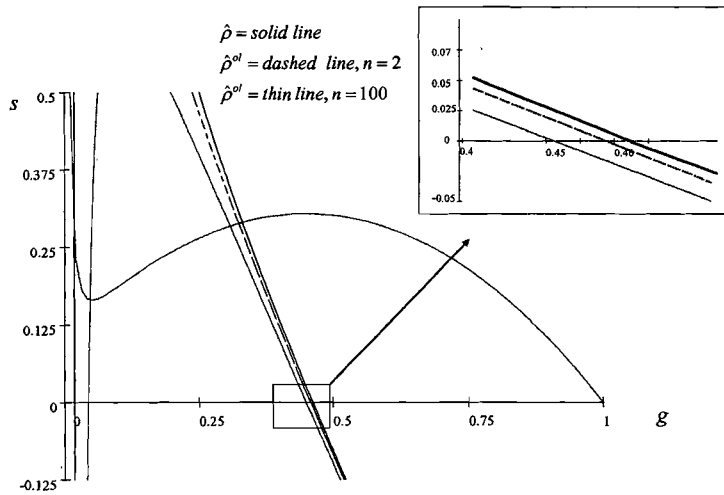


FIGURE 3. Critical discount rates, cooperation vs. open loop

internalize the positive externality of a stock reduction. Grazing has a large effect for these intermediate values of grass biomass, which implies that for non-cooperative farmers the cattle effect dominates, i.e. the steady state stock decreases. However for cooperative farmers the grass effect dominates, meaning that the steady state stock is increasing in the discount rate. Thus, the two management regimes respond differently (both in magnitude and direction) to a change in the discount rate and the conventional externality can be mitigated due to the grassland dynamics.

3.3. Markovian strategies. In an open-loop Nash equilibrium, farmers choose their strategies at the very beginning of the time span and stick to these. An open-loop strategy is a proper description of reality, if the farmers do not receive any new information in the course of the game. In most situations, this restriction may seem extreme, however. Consider instead the case when actions are conditioned on current time and only on the state variables. In such a case, the farmers are said to use Markovian strategies, and the solution concept is Markovian Nash equilibrium, which is characterized by subgame perfectness.

Suppose that the farmers use Markovian strategies and believe that so do the other farmers. This means that the farmers take into account that their opponents react

to changes in the state variables. Pontryagin's method is not well suited to solve such problems where new information can become available in the future, so dynamic programming is usually used instead.

The solution to such a problem requires advanced guesses about the value function, which is difficult here due to the non-linearities of the problem. In fact, we could not find any example of analytical solutions in the literature. The purpose of this section is not to derive a solution however, but merely to present the problem and discuss some possible directions of the potential solution.

Let $\eta_i(s,g)$ be the Markovian strategy of farmer i that expresses her harvest as a function of her own stock, the observed stock of the other farmers and the amount of grass available in the symmetric Markovian Nash equilibrium. Each farmer can observe the other farmers' stock and grass biomass at each point in time and use that information to update her strategy. At each point in time, the stock of farmer $j \neq i$ can be expressed as ψ_j. To simplify the notations, we let $\psi^{-i} = \sum_{j \neq i} \psi_j(s,g)$. Farmer i faces the following problem:

$$P_i = \max_{h_i} \int_0^{+\infty} \left(ph_i - c_1(h_i) - c_2 s_i\right) e^{-\rho t} dt \tag{3.18}$$

$$s.t. \quad :$$

$$\dot{s}_i = s_i b \frac{g^2}{x^2+g^2}\left(1 - \frac{s_i + \psi^{-i}}{k}\right) - h_i \tag{3.19}$$

$$\forall j \in I,\ j \neq i,\ \dot{s}_j = s_j b \frac{g^2}{x^2+g^2}\left(1 - \frac{s_i + \psi^{-i}}{k}\right) - \eta_j(s,g) \tag{3.20}$$

$$\dot{g} = (a+g)(1-g) - \left(s_i + \psi^{-i}\right)\frac{g^2}{x^2+g^2}. \tag{3.21}$$

Let $V^i(s,g)$ denote the optimal value of the objective functional of the problem, P_i. It satisfies the Hamilton-Jacobi-Bellman equation

$$\rho V^i(s,g) = \max_{h_i} \begin{array}{l} \Big\{ph_i - c_1(h_i) - c_2 s_i + V^{i\prime}_{s_i}(s,g)\left(s_i b \frac{g^2}{x^2+g^2}\left(1 - \frac{s_i+\psi^{-i}}{k}\right) - h_i\right) \\ \quad + \sum_{j \neq i} V^{i\prime}_{s_j}(s,g)\left(s_j b \frac{g^2}{x^2+g^2}\left(1 - \frac{s_i+\psi^{-i}}{k}\right) - \eta_j(s,g)\right) \\ \quad + V^{i\prime}_g(s_i,g)\left((a+g)(1-g) - \left(s_i+\psi^{-i}\right)\frac{g^2}{x^2+g^2}\right)\Big\}. \end{array} \tag{3.22}$$

If our game had been a linear-quadratic differential game, there would have existed an analytically tractable solution (also for the open-loop game) to this problem. But even for such games, it cannot be said in general whether open loop strategies or

Markovian strategies are better from the players' perspective, or if the Markovian Nash equilibrium is closer to the open-loop outcome or the cooperative outcome. For example, van der Ploeg and de Zeeuw (1992) show that the accumulated greenhouse gases are higher in the Markovian solution than in the open loop solution, the reason being that each country expects the other countries to reduce their emissions as a response to a higher amount of accumulated gases and therefore, each country loads more at the margin. Mäler and de Zeeuw (1998) also found this effect (although smaller) for an acid differential game applied to Europe. On the other hand, Tsuitsui and Mino (1990) show that if in a linear quadratic framework players are symmetric and there is a one dimensional state space, there exist non-linear Markovian strategies which are better from the players' perspective and which can even sustain a cooperative outcome.

4. Discussion

If grass is a fixed production factor, we confirm the standard result from the CPR literature that non-cooperative farmers exploit the grassland more than cooperative farmers, meaning that they keep larger stock sizes and grazing pressure than cooperative farmers. However, considering that grasslands are characterized by complex dynamics, we show this not to necessarily be the case.

From a policy perspective, it is important to realize that cooperative farmers will push the grassland to an alternate state if it is optimal for them to do so. Although the externalities associated with the common pool resource setting are internalized, the farmers only consider those benefits associated with grazing and there may be other services that the ecosystem can provide. Thus, the solution may not be the socially optimal. This has some policy implications; if a social planner observes degradation of a shared grassland and wishes to restore it, she cannot conclude that a cooperative solution will solve the problem. In fact, it might be better if the grassland were managed by non-cooperative farmers. Thus, assigning property rights by dividing the land may not be the best solution

Our results are obtained for farmers using open loop strategies, and there are limitations associated with those. The purpose of this paper is not to provide an analytical solution to the problem, however. Instead, the main contribution of this paper is to raise questions and doubts about the standard assumption adopted; i.e. that the resource shared is a fixed production factor, and we manage to do so for the simplest of information structures. Moreover, it could be true that open loop strategies are the better description of reality. As pointed out by Dockner et. al, open loop strategies may be attractive if farmers want to commit to certain strategies, due to environmental

concerns. There may also be other reasons why farmers do not change their strategies. For example, farmers might stick to strategies for cultural reasons or because of misperceptions.[16] Nevertheless, suppose that the cooperative solution is the socially optimal outcome and that one would like to know if the cooperative outcome can be sustained if farmers used Markovian strategies. Although this is not a repeated game, it is a dynamic one, and there might be such a solution, which would then constitute a Folk Theorem for the grazing game. Today, there exists no general Folk Theorem for differential games, although Gaitsgory and Nitzan (1994) have showed that under certain conditions, for example linear state equations, there does exist such a Theorem. However, we leave that exercise to future research.

[16] For example, concerning reindeer management in the Nordic countries (where there is often a commons problem present) it has been observed that due to reindeer grazing, there has been a drastic change in the state of nature, a degradation of vegetation. Still, reindeer managers do not react to this change but rather keep the same management strategies as before (Moen and Danell, 2003, Moxnes, 1998).

Appendix

Simplification and scaling

$$\frac{dS}{dt} = \varepsilon BS\frac{G^2}{X^2+G^2}\left(1-D\frac{S}{K}\right) - H \tag{A1}$$

$$\frac{dG}{dt} = U\left(A+G\right)\left(1-\frac{G}{C}\right) - BS\frac{G^2}{X^2+G^2} \tag{A2}$$

Let u_S, u_G and u_t be cattle, grass and time measurement units so that $s = \frac{S}{u_S}$, $h = \frac{Hu_t}{u_S}$, $g = \frac{G}{u_G}$, and $\tau = \frac{t}{u_t}$ represents dimensionless variables of cattle, harvest grass biomass and time, respectively

$$\dot{s} = \frac{\partial s}{\partial \tau} = \frac{\frac{\partial S}{\partial t}}{u_s}u_t = u_t\varepsilon Bs\frac{g^2}{\left(\frac{X}{u_G}\right)^2+g^2}\left(1-D\frac{su_s}{K}\right) - h \tag{A3}$$

$$\dot{g} = \frac{\partial G}{\partial \tau} = \frac{\frac{\partial G}{\partial t}}{u_G}u_t = u_tU\left(\frac{A}{u_G}+g\right)\left(1-\frac{gu_g}{C}\right) - \frac{u_t}{u_g}Bsu_s\frac{g^2}{\left(\frac{X}{u_G}\right)^2+g^2}. \tag{A4}$$

We are now free to choose convenient measurement units, thus let $u_t = \frac{1}{U}$, $u_g = C$ and $u_s = \frac{CU}{B}$

$$\dot{s} = \frac{\varepsilon B}{U}s\frac{g^2}{\left(\frac{X}{C}\right)^2+g^2}\left(1-D\frac{sCU}{BK}\right) - h \tag{A5}$$

$$\dot{g} = \left(\frac{A}{C}+g\right)(1-g) - s\frac{g^2}{\left(\frac{X}{C}\right)^2+g^2}. \tag{A6}$$

Then, define new parameters, let $b = \frac{\varepsilon B}{U}$, $x = \frac{X}{C}$, $a = \frac{A}{C}$ and $k = \frac{BK}{DCU}$. This yields the below system

$$\dot{s} = bs\frac{g^2}{x^2+g^2}\left(1-\frac{s}{k}\right) - h \tag{A7}$$

$$\dot{g} = (a+g)(1-g) - s\frac{g^2}{x^2+g^2}. \tag{A8}$$

Motivation for phase diagram

We have that:

$$s|_{\dot{g}=0} = S_{\varphi}(g, a, b, x) = (a+g)(1-g)\frac{(x^2+g^2)}{g^2}. \tag{A9}$$

The sign of the derivative,

$$\frac{\partial S_{\varphi}(g, a, b, x)}{\partial g} = -\frac{2(g^4+ax^2)-(1-a)(g^2-x^2)g}{g^3}, \tag{A10}$$

depends on parameter values. More specifically, the derivative is negative if

$$2(g^4+ax^2)-(1-a)(g^2-x^2)g > 0. \tag{A11}$$

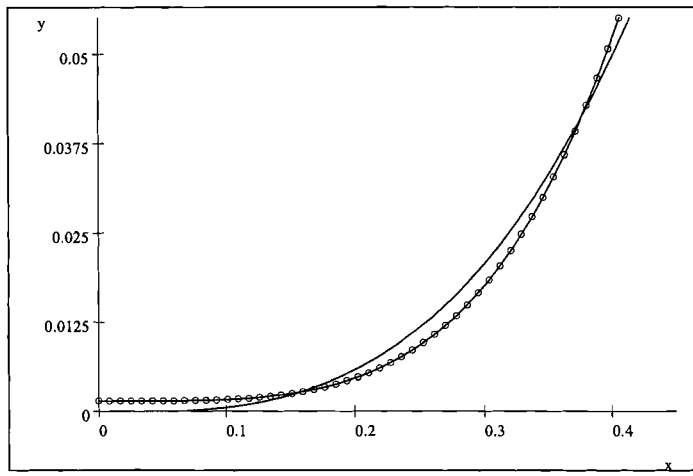
Let $\alpha(g) = 2(g^4+ax^2)$ and $\beta(g) = (1-a)(g^2-x^2)g$. It is easily verified that $\alpha(g)$ is increasing and convex for any positive value of a and x, and $\alpha(0) = 2ax^2$. For $\beta(g)$ we have that

$$\frac{\partial \beta}{\partial g} = (3g^2-x^2)(1-a) \tag{A12}$$

$$\frac{\partial^2 \beta}{\partial g^2} = 6g(1-a). \tag{A13}$$

The graph of β depends on parameter values. But if we follow Jensen, Anderies and Walker, the tiller potential a should be lower than 1. This implies that β has a minimum at $g = \frac{\sqrt{3}}{3}x = \check{g}$ and is convex. Moreover, $\beta(0) = \beta(x) = 0$ and $\beta(\check{g}) = -\frac{2}{9}(1-a)x^3\sqrt{3}$. From this, we can conclude that α and β can intersect if x is sufficiently small as compared to a. This means that there will be an interval on which $\left.\frac{ds}{dg}\right|_{\dot{g}=0}$ is positive for intermediate values of g. If grass biomass is small or if grass biomass is large, $\left.\frac{ds}{dg}\right|_{\dot{g}=0}$ is negative. (see Figure 4 where the dotted line represents the graph of $\alpha(g)$ and the plain line the graph of $\beta(g)$).

If x is large compared to a, the curves do not intersect and $\left.\frac{ds}{dg}\right|_{g=0} < 0$ for any grass biomass level. Note also that $\lim_{g\to 0} S_\varphi(g,a,b,x) = +\infty$, and $S_\varphi(1,a,b,x) = 0$.



($a = 0.2$ and $x = 0.06$)

If $x = 0$, the function $S_\varphi(g,a,b,x)$ has a maximum for $\bar{g} = \frac{1}{2}(1-a) < \frac{1}{2}$ since $a > 0$. If $x > 0$ and $S_\varphi(g,a,b,x)$ is convex-concave, $S_\varphi(g,a,b,x)$ has a local maximum and a local minimum for $\alpha(g) = \beta(g)$. We would like to show that these local extrema occur for $g < \bar{g}$. Note that

$$\frac{\partial S_\varphi(g,a,b,x)}{\partial x} = (a+g)(1-g)\frac{2x}{bg^2} \tag{A14}$$

is non-negative for all grass biomasses, $g \in [0,1]$, so that the steady state locus "shifts upward" for positive values of x. Also,

$$\frac{\partial S_\varphi\left(\frac{1}{2}(1-a),a,b,x\right)}{\partial g} = 4x^2\frac{(1+a)^2}{b(a-1)^3} < 0, \tag{A15}$$

so there must exist a grass stock $g < \bar{g}$ that yields a higher stock of cattle when $x > 0$. Furthermore, we can show that $\frac{\partial S_\varphi(g,a,b,x)}{\partial x} < 0$ for all $g > \bar{g}$:

$$\text{(A16)} \qquad \frac{\partial S_\varphi(g,a,b,x)}{\partial x} < 0 \Leftrightarrow 2\left(g^4 + ax^2\right) - (1-a)\left(g^2 - x^2\right) g > 0.$$

Note that

$$\text{(A17)} \qquad \begin{aligned} &2\left(g^4 + ax^2\right) - (1-a)\left(g^2 - x^2\right) g > 2g^4 - (1-a)\left(g^2 - x^2\right) g \\ &> 2g^3 - (1-a)\left(g^2 - x^2\right) > 2g^3 - (1-a)\, g^2 > 2g - (1-a)\,, \end{aligned}$$

and

$$\text{(A18)} \qquad 2g - (1-a) > 0 \Leftrightarrow g > \frac{1}{2}(1-a)$$

so

$$\text{(A19)} \qquad g > \frac{1}{2}(1-a) \Rightarrow \frac{\partial S_\varphi(g,a,b,x)}{\partial x} < 0.$$

This implies that if S_φ has a local maximum, it must occur for values of $g < \bar{g}$. Let

$$\text{(A20)} \qquad S_\phi(g,h,r) = \frac{k}{2}\left(1 + \sqrt{1 - \frac{4h}{bk}\frac{x^2+g^2}{g^2}}\right).$$

We can note that $\frac{\partial S_\phi(g,h,r)}{\partial g} > 0$ and that $S_\phi(1,h,r) = \frac{k}{2}\left(1 + \sqrt{1 - \frac{4h}{bk}\left(x^2+1\right)}\right)$.

The static model

In cooperation, the farmers maximize the joint-profit given condition (A21) on rivalry[17]

$$s_i = \frac{k}{2n}\left(1+\sqrt{1-\frac{4nh_i}{kb}\frac{(x^2+g^2)}{g^2}}\right). \tag{A21}$$

Note that the constraint (A21) implies that harvest is uniquely determined once a stock size is given, so that this problem is equivalent to finding the stock size that will maximize harvest profit. Equation (A21) can be rewritten as (A22)

$$h_i = ns_i b\frac{g^2}{x^2+g^2}\left(1-\frac{ns_i}{k}\right). \tag{A22}$$

The maximization problem for cooperative farmers is given by:

$$\max_{s_i} n\left(ps_i b\frac{g^2}{x^2+g^2}\left(1-\frac{ns_i}{k}\right)-c_1\left(s_i b\frac{g^2}{x^2+g^2}\left(1-\frac{ns_i}{k}\right)\right)-c_2 s_i\right). \tag{A23}$$

We let c_1' denote the first derivative of c_1, the first-order condition is

$$\left(p-c_1'\left(h_i\right)\right)b\left(\frac{g^2}{x^2+g^2}\left(1-\frac{2ns_i}{k}\right)\right)-c_2=0, \tag{A24}$$

which means that:

$$ns_i^{co} = \frac{1}{2}k\left(1-\frac{x^2+g^2}{g^2}\frac{c_2}{b\left(p-c_1'\left(h_i^{co}\right)\right)}\right). \tag{A25}$$

Similarly, the maximization problem for non-cooperative farmers is:

[17] As before, two equations solve equation (2.7a) but only the solution (A21) captures rivalry, because only then is $\frac{\partial s_i}{\partial n} < 0$.

$$\text{(A26)} \quad \max_{s_i} ps_i b \frac{g^2}{x^2+g^2}\left(1-\frac{s_i+\Psi^{-i}}{k}\right) - c_1\left(s_i b \frac{g^2}{x^2+g^2}\left(1-\frac{s_i+\Psi^{-i}}{k}\right)\right) - c_2 s_i.$$

Using the same technique as for cooperation, we get

$$\text{(A27)} \qquad ns_i^{no} = \frac{n}{(n+1)} k\left(1-\frac{x^2+g^2}{g^2}\frac{c_2}{b\left(p-c_1'\left(h_i^{no}\right)\right)}\right).$$

Note that a larger harvest level is associated with the smaller stock $\frac{\partial ns_i^{no}}{\partial h_i^{no}} < 0$, $\frac{\partial ns_i^{co}}{\partial h_i^{co}} < 0$. Moreover, a positive stock, ($ns_i^{no} > 0$, or $ns_i^{co} > 0$) requires

$$\text{(A28)} \qquad \frac{\left(x^2+g^2\right)}{bg^2} c_2 < \left(p-c_1'\left(h_i\right)\right).$$

Note that

$$\text{(A29)} \qquad \left(p-c_1'\left(h_i\right)\right) = \frac{(n-1)\left(p-c_1'\left(h_i\right)\right)\left(p-c_1'\left(h_i\right)\right)}{2n\left(p-c_1'\left(h_i\right)\right)-(n+1)\left(p-c_1'\left(h_i\right)\right)}.$$

Suppose first that $h_i^{no} > h_i^{co} \Longleftrightarrow \left(p-c_1'\left(h_i^{no}\right)\right) < \left(p-c_1'\left(h_i^{co}\right)\right)$, then we must have that the cattle stock in cooperation is higher than in noncooperation. It must then hold that

$$\text{(A30)} \quad \frac{n}{(n+1)} k\left(1-\frac{x^2+g^2}{g^2}\frac{c_2}{b\left(p-c_1'\left(h_i^{no}\right)\right)}\right) < \frac{1}{2} k\left(1-\frac{x^2+g^2}{g^2}\frac{c_2}{b\left(p-c_1'\left(h_i^{co}\right)\right)}\right),$$

which can only hold if

$$\text{(A31)} \qquad \frac{x^2+g^2}{bg^2} c_2 > \frac{(n-1)\left(p-c_1'\left(h_i^{no}\right)\right)\left(p-c_1'\left(h_i^{co}\right)\right)}{\left(2n\left(p-c_1'\left(h_i^{co}\right)\right)-(n+1)\left(p-c_1'\left(h_i^{no}\right)\right)\right)}.$$

Suppose next that $h_i^{no} = h_i^{co} \Longleftrightarrow \left(p-c_1'\left(h_i^{no}\right)\right)) = \left(p-c_1'\left(h_i^{co}\right)\right)$. Then, we can note that the cattle stock in cooperation is higher if

$$\text{(A32)} \qquad \frac{x^2+g^2}{bg^2}c_2 > \left(p - c_1'\left(h_i^{co}\right)\right),$$

which is inconsistent with a positive stock. Moreover, because

$$\text{(A33)} \qquad \frac{\partial}{\partial\left(p-c_1'\left(h_i^{co}\right)\right)}\left(\frac{(n-1)\left(p-c_1'\left(h_i^{no}\right)\right)\left(p-c_1'\left(h_i^{co}\right)\right)}{\left(2n\left(p-c_1'\left(h_i^{co}\right)\right)-(n+1)\left(p-c_1'\left(h_i^{no}\right)\right)\right)}\right) = -\frac{(n-1)\left(p-c_1'\left(h_i^{no}\right)\right)(1+n)\left(p-c_1'\left(h_i^{no}\right)\right)}{\left(2n\left(p-c_1'\left(h_i^{co}\right)\right)-(1+n)\left(p-c_1'\left(h_i^{no}\right)\right)\right)^2} < 0.$$

We can conclude that given the condition of positive stocks (A28), and from (A31) and (A33) the harvest level cannot be higher for cooperative farmers. Now, suppose instead that $h_i^{co} > h_i^{no}$ applying the same technique, we must have that

$$\text{(A34)} \qquad \frac{n}{(n+1)}k\left(1-\frac{x^2+g^2}{g^2}\frac{c_2}{b\left(p-c_1'\left(h_i^{no}\right)\right)}\right) > \frac{1}{2}k\left(1-\frac{x^2+g^2}{g^2}\frac{c_2}{b\left(p-c_1'\left(h_i^{co}\right)\right)}\right),$$

which holds if

$$\text{(A35)} \qquad \frac{x^2+g^2}{bg^2}c_2 < \left(\frac{(n-1)\left(p-c_1'\left(h_i^{no}\right)\right)\left(p-c_1'\left(h_i^{co}\right)\right)}{2n\left(p-c_1'\left(h_i^{co}\right)\right)-(n+1)\left(p-c_1'\left(h_i^{no}\right)\right)}\right)$$

and because

$$\text{(A36)} \qquad \frac{\partial}{\partial\left(p-c_1'\left(h_i^{no}\right)\right)}\left(\frac{(n-1)\left(p-c_1'\left(h_i^{no}\right)\right)\left(p-c_1'\left(h_i^{co}\right)\right)}{2n\left(p-c_1'\left(h_i^{co}\right)\right)-(n+1)\left(p-c_1'\left(h_i^{no}\right)\right)}\right) = \frac{2(n-1)\left(-\left(p-c_1'\left(h_i^{co}\right)\right)\right)^2 n}{\left(2n\left(-\left(p-c_1'\left(h_i^{co}\right)\right)\right)+\left(p-c_1'\left(h_i^{no}\right)\right)(1+n)\right)^2} > 0$$

it holds. From this, we can conclude that for the static case, cooperative farmers keep higher harvest levels and lower stocks than non-cooperative farmers.

Concavity conditions

The maximized Hamiltonean, $\hat{H}(s,g,\lambda_i,\mu) \equiv \mathcal{H}(h^*,s,g,\lambda_i,\mu)$ is concave in s and g if $(-1)^r \triangle_r \geq 0$ for $r = 1,2$, where $\triangle_r$ are principal minors of the order r in the Hessian for $\hat{H}(s,g,\lambda_i,\mu)$ (see Nikaido 1968). We have that $h_i^*(\lambda_i) = ((c_1')^{-1}(p-\lambda_i))$, so from symmetry

$$\text{(A37)} \qquad \begin{aligned}\hat{H}(s,g,\lambda_i,\mu) = {} & np\left((c_1')^{-1}(p-\lambda_i)\right) - nc_1\left((c_1')^{-1}(p-\lambda_i)\right) - c_2 s \\ & + \lambda_i\left(sb\frac{g^2}{x^2+g^2}\left(1-\frac{s}{k}\right) - n\left((c_1')^{-1}(p-\lambda_i)\right)\right) \\ & + \mu\left((a+g)(1-g) - sb\frac{g^2}{x^2+g^2}\right),\end{aligned}$$

the corresponding Hessian is $\begin{pmatrix}\hat{H}_{ss} & \hat{H}_{sg} \\ \hat{H}_{sg} & \hat{H}_{gg}\end{pmatrix}$, where

$$\text{(A38)} \qquad \hat{H}_{ss} = -2\lambda_i\frac{g^2}{(x^2+g^2)}\frac{b}{k} < 0$$

$$\text{(A39)} \qquad \hat{H}_{sg} = \hat{H}_{gs} = \lambda_i\frac{2gx^2}{(x^2+g^2)^2}b\left(1-\frac{2s}{k}\right) - \mu b\frac{2gx^2}{(x^2+g^2)^2}$$

$$\text{(A40)} \qquad \hat{H}_{gg} = -2\lambda_i sb\left(1-\frac{s}{k}\right)\frac{(3g^2-x^2)\,x^2}{(x^2+g^2)^3} - 2\mu\left(1+sb\frac{(3g^2-x^2)\,x^2}{(x^2+g^2)^3}\right)$$

A concave Hamiltonian requires

$$\text{(A41)} \qquad \lambda_i \geq 0$$

$$\text{(A42)} \qquad \left(-2\lambda_i\frac{g^2}{(x^2+g^2)}\frac{b}{k}\right)\hat{H}_{gg} - \left(\lambda_i\frac{2gx^2}{(x^2+g^2)^2}b\left(1-\frac{2s}{k}\right) - \mu b\frac{2gx^2}{(x^2+g^2)^2}\right)^2 \geq 0,$$

which means that

$$\text{(A43)} \qquad -\frac{\left(\lambda_i\frac{2gx^2}{(x^2+g^2)^2}b\left(1-\frac{2s}{k}\right) - \mu b\frac{2gx^2}{(x^2+g^2)^2}\right)^2}{2\lambda_i\frac{g^2}{(x^2+g^2)}\frac{b}{k}} \geq \hat{H}_{gg}.$$

PROOF OF LEMMA 1. We have that;

$$\frac{\mu}{(p-c_1'(h_i))}=\frac{(kg^2-(a+g)(1-g)(x^2+g^2))\,2x^2(a+g)(1-g)}{bkg^2(g(\rho-1+2g+a)(x^2+g^2)+(a+g)(1-g)2x^2)}. \tag{A44}$$

First, note that in a steady state with positive harvest and stock, it must be true that the steady-state stock of cattle is lower than the carrying capacity, $s<k$. Furthermore, note that in steady state

$$s=(a+g)(1-g)\frac{(x^2+g^2)}{g^2}, \tag{A45}$$

which means that

$$\left(kg^2-(a+g)(1-g)\left(x^2+g^2\right)\right)>0. \tag{A46}$$

This implies that $\mu>0$ if

$$g(\rho-1+2g+a)\left(x^2+g^2\right)-(a+g)(1-g)2x^2>0 \tag{A47}$$

which is true if

$$\rho>1-2g-a-\frac{2(a+g)(1-g)}{g}\frac{x^2}{(x^2+g^2)}. \tag{A48}$$

Then note that

$$1-2g-a-\frac{2(a+g)(1-g)}{g}\frac{x^2}{(x^2+g^2)}>0 \tag{A49}$$

only if

$$(1-2g-a)\left(x^2+g^2\right)g-2(a+g)(1-g)x^2>0 \tag{A50}$$

which is true only if

$$g^3-2g^4-ag^3-gx^2+agx^2>2x^2a. \tag{A51}$$

Recall that we only find stable steady states on the decreasing part of $S_\varphi(g,a,b,x)$, which is true if

$$2\left(g^4+ax^2\right)-(1-a)\left(g^2-x^2\right)g>0 \tag{A52}$$

which holds only if

$$2ax^2 > g^3 - 2g^4 - ag^3 - gx^2 + agx^2 \tag{A53}$$

Comparing equation A50 with A52 we can conclude that for positive values of discount factors, μ is positive in steady state. Finally, note that

$$\frac{\partial \mu}{\partial \rho} = -\frac{\left(kg^2 - (a+g)(1-g)(x^2+g^2)\right)2x^2(a+g)(1-g)(x^2+g^2)}{bkg\left(g(\rho-1+2g+a)(x^2+g^2)+(a+g)(1-g)2x^2\right)^2} < 0. \tag{A54}$$

□

PROOF OF PROPOSITION 1. The steady-state stock is given by

$$s^{*co} = \frac{k}{2}\left(1 - \frac{c_2}{(p - c_1'(h_i))}\frac{x^2+g^2}{bg^2} - \rho\frac{x^2+g^2}{bg^2} - \frac{\mu}{(p - c_1'(h_i))}\right). \tag{A55}$$

Taking the derivative of the steady-state stock with respect to the discount rate, we obtain

$$\frac{k(x^2+g^2)}{2bg^2}\left(\frac{\left(kg^2 - (a+g)(1-g)(x^2+g^2)\right)2x^2(a+g)(1-g)}{k\left(g(\rho-1+2g+a)(x^2+g^2)+(a+g)(1-g)2x^2\right)^2} - 1\right). \tag{A56}$$

This is positive if

$$\frac{\left(kg^2 - (a+g)(1-g)(x^2+g^2)\right)2x^2(a+g)(1-g)}{k\left(g(\rho-1+2g+a)(x^2+g^2)+(a+g)(1-g)2x^2\right)^2} > 1, \tag{A57}$$

which holds if

$$\rho < \hat{\rho}(a,x,k,g) = 1 - 2g - a - \frac{(a+g)(1-g)2x^2}{g(x^2+g^2)} + \frac{1}{g(x^2+g^2)}\left(\sqrt{\frac{\left(kg^2 - (a+g)(1-g)(x^2+g^2)\right)2x^2(a+g)(1-g)}{k}}\right). \tag{A58}$$

□

PROOF OF LEMMA 2. First note that $\mu^{ol} = n\mu$, because $\mu > 0$ and $\frac{\partial \mu}{\partial \rho} < 0$ we can conclude that $\mu^{ol} > 0$ and $\frac{\partial \mu^{ol}}{\partial \rho} < 0$. □

PROOF OF PROPOSITION 2. The steady-state stock in non-cooperation is given by:

$$s^{*no} = \frac{n}{(n+1)} k \left(1 - \frac{c_2}{(p - c_1'(h_i))} \frac{x^2 + g^2}{bg^2} - \rho \frac{x^2 + g^2}{bg^2} - \frac{\mu^{ol}}{(p - c_1'(h_i))} \right). \tag{A59}$$

Taking the derivative with respect to discount rate, we obtain

$$\frac{n}{(n+1)} \frac{(x^2 + g^2)}{bg^2} k \left(\frac{(kg^2 - (a+g)(1-g)(x^2+g^2)) 2x^2 (a+g)(1-g)}{nk (g(\rho - 1 + 2g + a)(x^2+g^2) + (a+g)(1-g) 2x^2)^2} - 1 \right), \tag{A60}$$

which is positive if

$$\frac{(kg^2 - (a+g)(1-g)(x^2+g^2)) 2x^2 (a+g)(1-g)}{nk (g(\rho - 1 + 2g + a)(x^2+g^2) + (a+g)(1-g) 2x^2)^2} > 1, \tag{A61}$$

which holds if

$$\rho < \hat{\rho}^{ol}(a, x, k, g) = 1 - 2g - a - \frac{(a+g)(1-g) 2x^2}{g(x^2+g^2)} + \frac{1}{g(x^2+g^2)} \left(\sqrt{\frac{(kg^2 - (a+g)(1-g)(x^2+g^2)) 2x^2 (a+g)(1-g)}{nk}} \right). \tag{A62}$$

Now, it is easily verified that $\hat{\rho}^{ol}(a, x, k, g) < \hat{\rho}(a, x, k, g)$. □

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PAPER 4

Who Wants to Save the Baltic Sea?

Therese Lindahl and Tore Söderqvist

ABSTRACT. Recent research shows that the Baltic Sea has experienced an ecosystem change and is now in a degraded state. Moreover, it is uncertain whether this deterioration is reversible. We use the referendum approach asking people to vote on a hypothetical abatement program with the purpose of improving the marine water quality of the Baltic Sea where the program is only successful with a certain probability. Our mixed results could have important policy implications as the answer to the question depends very much on how we ask.

IV

1. Introduction

Today, a lot of resources are spent in order to recover degraded ecological systems. Simultaneously there exists empirical evidence that there are ecosystems which have been degraded to the point where it is uncertain whether a healthy state can be recovered at all (Resilience Alliance, 2005). On the other hand if no measures are taken these ecosystems may reach even worse states. A natural question emerges; should resources be devoted to the purpose of restoring such ecosystems?

In light of this, the aim of this paper is to empirically analyze how people respond to the potential irreversibility of environmental degradation when considering whether environmental programs should be launched or not.

Our case study is the highly vulnerable and disturbed marine ecosystem of the Baltic Sea. Recent research shows that it is uncertain whether a healthy state of the Baltic Sea can be recovered; there is a risk that the ecosystem cannot be restored, regardless of measures taken (Swedish Environmental Advisory Council, 2005).

To elicit people's preferences towards environmental improvements one often needs to rely on stated preferences methods (Freeman, 2003). We follow this approach and design a referendum type of questionnaire where randomly selected individuals are

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asked to vote on a hypothetical abatement program. The purpose of the program is to improve the marine water quality of the Stockholm Archipelago, a part of the Baltic Sea. The program is characterized by success uncertainty, meaning that the program will have the intended effect only with a certain probability. We use two procedures for introducing uncertainty; a between-sample design where each respondent is asked to vote being informed about one out of five success probabilities, and a within-sample design where each respondent is asked to put a vote to each of the five success probabilities.

Our design resembles tests of scope sensitivity of the contingent valuation method (CVM), a stated preferences method widely used for eliciting willingness to pay for public goods. These tests try to find out whether CVM results show sensitivity to variations in quantity and quality of the good being valued. Scope sensitivity is a hot topic and has been the focus of much debate.[1] Ever since the distinguished NOAA panel (Arrow et al. 1993) recommended, inter alia, scope tests, numerous such tests have been conducted, using both between-sample and within-sample approaches with mixed results.[2] However, as far as we understand none of these studies has tested for sensitivity to scope in relation to the probability of program success.

Our study does not aim at estimating willingness to pay, but is rather motivated by the growing literature that ecosystems often entail quite complex dynamics and as a consequence, measures taken to improve the quality of these ecosystems may not necessarily have the intended effect. We believe it is important to understand how people respond to this type of uncertainty, not least for the design of CVM studies involving uncertain provisions of public goods. As indicated by our results, the answer is not obvious.

We proceed as follows. The next section describes the ecological background and our data. In Section 3 we present the empirical model used. The results are presented in Section 4 and a discussion and some concluding remarks are given in Section 5.

[1] This issue reached a peak when the State Government of Alaska filed suits against Exxon Corporation claiming damages following the grounding of Exxon Valdez in 1989. The claims were based on CVM - generated estimates of the costs incurred as a result of the oil-spill. (For overviews and discussions of the CVM see Portney, 1994; Hanemann, 1994; Diamond and Hausman, 1994; Carson et al., 2001; Freeman, 2003.)

[2] See for example Carson's (1997) survey of 30 CVM studies where he concludes that only in a handful of them were respondents not sensitive to scope. These studies were mainly within-sample tests. For between-sample tests, see for example the meta analysis by Smith and Osborne (1996), or the study by Svedsäter (2000). Whereas the former found sensitivity to scope the latter did not.

2. Empirical background

2.1. The problem. In the traditional resource management literature the resource exploited is assumed to be properly characterized by some concave growth function. Today there exists an extensive amount of empirical evidence that many ecosystems have more complex dynamics and that growth functions are typically not concave but rather convex-concave. This means that they can have multiple stable states with separate domains of attraction. A typical feature of such ecosystems is that they can undergo sudden changes and flip from one state to another. Due to positive feedback effects, a state can become highly robust and sometimes the change may even be irreversible. This may be problematic, especially if one wishes to restore the ecosystem. There are many ecosystems that fit this description on a global, regional as well as a local scale.[3]

One such ecosystem is the Baltic Sea. With the moderate age of 10-15,000 years, the Baltic Sea is the youngest sea on the planet. It is the second largest body of brackish water with many unique species. However, such a salinity level creates unfavorable conditions for many aquatic organisms, which makes the sea highly vulnerable. At the same time 85 million people live in the catchment area of the Baltic Sea and due to pollutants and nutrients from land-based activities, such as wastewater, agriculture, industry and traffic, there is a lot of stress on this ecosystem.

The Baltic Sea has two stable ecological states (Resilience Alliance, 2005). One state, the clear state, is associated with relatively clear water, submerged vegetation and preferred fish species. Due to substantial increases in anthropogenic nutrient loads, the amount of dissolved oxygen in the water has decreased. In addition, low inflow of water from the North Sea makes the water turnover slow (in the order of 20 years), which implies that the high levels of phosphorus and nitrogen stay within the system. As a result there has been a shift in the ecosystem from the clear steady state to a eutrophic steady state, associated with toxic algae blooms, relatively turbid water, oxygen deficiency and less preferred fish species. Today the Baltic Sea is one of the most threatened marine ecosystems on the planet; no less than 88% of the biotopes found in the Baltic Sea are listed as endangered (Resilience Alliance, 2005).

An international agreement in 1988 involved abatement programs aiming at reducing the nutrient load by half by 1995 (Swedish Cabinet Bill 1990/91:90). This goal was not achieved and additional efforts have been suggested and to some extent carried out (Swedish EPA 2003).

[3] Such resources have only recently been considered in the economic literature. For a more general economic discussion of such resources see Dasgupta and Mäler (2003).

However, recent research shows that it is uncertain whether the change in the ecosystem is reversible; there is a risk that the Baltic Sea cannot be restored to a clear state, regardless of measures taken (Swedish Environmental Advisory Council, 2005).

2.2. Data. A mail survey was designed for collecting data about people's behavior when asked to vote on a hypothetical abatement program with the purpose to improve the marine water quality of the Stockholm Archipelago. The questionnaire was received by in total 4,000 randomly selected adult inhabitants in the county where the archipelago is situated (Stockholm County) and in one adjacent county (Uppsala County). It was sent out after the summers of 1998 and 1999 and the overall response rate was about 50 percent. The voting scenarios for the between-sample and within-sample designs are found in the Appendix. Both designs included a description of the abatement program. The program involved measures in the agricultural and municipal sectors that with some X-percent probability would result in water quality improvements manifested by a 1-meter increase in the average water transparency. If launched, the program would entail price increases for products produced by these sectors.[4] The ongoing deterioration of the water quality would continue if the program turns out not to be successful. The voting question was formulated as follows. *Would you accept or not accept to pay something in terms of increased expenses in order to make it possible to carry out this abatement program?* The respondents were given three mutually exclusive alternatives; *I would definitely accept, I would probably accept and I would not accept.*

The sampled individuals were randomly grouped in six sub-samples. Five of these were used for the between-sample design, where each individual faced one of the following five success probabilities; {0.1, 0.25, 0.5, 0.75, 0.9}. The remaining sub-sample was used for the within-sample design, where each individual faced all five success probabilities and was asked to put a vote to each of them. Some descriptive statistics are given in Table 1.[5] The respondents are between 16 and 78 years with an average of about 50 years. About 55 percent are female, 8 percent are residents in the archipelago, 20 percent report to own a cottage in the archipelago or that someone in their family owns a cottage, and 13 percent live in Uppsala County. The average personal monthly income (including unemployment benefits, child support, student loans etc. and after

[4] A tax as a payment vehicle was found in a pilot study to result in a large proportion of protest answers.

[5] Note that each respondent answers five questions in the within-sample design and these answers are here treated as different observations. The dummy variables were coded as follows; 1 for residence in the archipelago, 0 otherwise; 1 for visitor in the archipelago, 0 otherwise; 1 for cottage in the archipelago, 0 otherwise; 1 for female respondent, 0 otherwise; 1 for residence in Uppsala County, 0 otherwise. The variable age is given in years and income is net personal income per month in SEK.

tax) is about SEK 12,800. About 43 % voted *definitely*, 46% voted *probably* and about 11% voted *no*.

Table 1. Descriptive Statistics

variable	N	mean	stdv.	min	max
resident	1 864	0.079	0.270	0	1
cottage	1 858	0.203	0.403	0	1
visit	1 860	0.584	0.493	0	1
female	1 898	0.547	0.498	0	1
age	1 892	49.7	13.8	16	78
income	1 790	12 823	7 087	0	100 000
U. County	1 899	0.125	0.331	0	1
definitely	2 483	0.432	0.495	0	1
probably	2 483	0.456	0.498	0	1
no	2 483	0.112	0.315	0	1

In a real referendum, people are generally informed about the referendum beforehand; the question has appeared in media and there are usually broadcast debates on the issue. In hypothetical referenda this is usually not the case. However, the Stockholm County is one of the most densely populated area found on the Baltic Sea coast and due to its many attractive features, the Stockholm Archipelago is one of the largest recreational areas. As a result of excess nutrients this area is affected by periodic algae blooms, now more frequently than ever (Swedish Environmental Advisory Council, 2005). This fact, and periodically considerable media attention to eutrophication issues are likely to imply that people living in and visiting this area are quite familiar with the problems of eutrophication.

3. Empirical strategy

Each respondent is facing three alternatives. The discrete choice of each individual i is based on the person's own marginal benefit - marginal cost calculation, which partly depends on unobservable factors specific to the individual. Motivated by three response alternatives, where *I would not accept*, *I would probably accept* and *I would definitely accept* are coded 0, 1 and 2 respectively, we will use an ordered discrete choice model (Zavoina and McElvey, 1975) to analyze the data. The model is built around a latent regression, where the underlying response model is given by equation (3.1).

$$y_i^* = \boldsymbol{\beta}'\mathbf{x}_i + \epsilon_i \tag{3.1}$$

Note that y_i^* is not observable, but what we do observe from respondents' answers is

$$\begin{aligned} y_i &= 0 \quad \text{if } y_i^* \leq 0; \\ y_i &= 1 \quad \text{if } 0 < y_i^* \leq \mu; \\ y_i &= 2 \quad \text{if } \mu < y_i^*. \end{aligned}$$

The parameter μ is an unknown threshold parameter to be estimated along with a coefficient vector $\boldsymbol{\beta}$. In this model, a positive (negative) coefficient means that the probability of acceptance increases (decreases). $\boldsymbol{\epsilon}$ is assumed to be normally distributed with mean 0 and variance 1. Thus we have that

$$\begin{aligned} \Pr(y_i = 0) &= \Pr(\boldsymbol{\beta}'\mathbf{x}_i + \boldsymbol{\epsilon}_i \leq 0) = 1 - \Phi(\boldsymbol{\beta}'\mathbf{x}_i); \\ \Pr(y_i = 1) &= \Pr(0 < \boldsymbol{\beta}'\mathbf{x}_i + \boldsymbol{\epsilon}_i \leq \mu) = \Phi(\mu - \boldsymbol{\beta}'\mathbf{x}_i) - \Phi(-\boldsymbol{\beta}'\mathbf{x}_i); \\ \Pr(y_i = 2) &= \Pr(\mu < \boldsymbol{\beta}'\mathbf{x}_i + \boldsymbol{\epsilon}_i) = 1 - \Phi(\mu - \boldsymbol{\beta}'\mathbf{x}_i); \end{aligned}$$

where Φ is the standard normal cumulative distribution function. The probability that a person falls into any one of these categories depends on a vector of decision variables $\mathbf{x}_i$. Estimation is done by maximum likelihood.

We test the effect of reversibility, i.e. the probability of a successful program, by running the ordered probit model for the between-sample design. The within-sample design is analyzed by a random effects ordered probit model which is built around the regression

$$y_{ip}^* = \boldsymbol{\beta}'\mathbf{x}_{ip} + \boldsymbol{\epsilon}_{ip} + \mathbf{u}_p, \tag{3.2}$$

where p denotes probability. The term $\mathbf{u}_p$ is normally distributed with mean 0 and variance, σ^2. This is appropriate because of the panel nature of the within-sample design, where each respondent makes five votes. If we were to use the same method as for the between-sample design it could lead to biased estimates.

The decision variables included in $\mathbf{x}_i$ (and $\mathbf{x}_{ip}$) are dummies for the probabilities of reversibility (denoted as d10, d25, d50, d75 and d90), income, age and dummy variables for females, residence in Uppsala County and visit to the archipelago during the summer. The Uppsala County dummy should have a significantly negative influence if improved water quality is primarily associated with use values rather than non-use values. By similar argument we expect the visit dummy to have a significantly positive influence. We will thus test the following model;

$$\Pr(y_i = 2) = f(\textit{income}, \textit{reversibility}, \textit{U County}, \textit{visit}, \textit{age}, \textit{gender}). \tag{3.3}$$

4. Results

The overall voting behavior is reported in Table 2, where respondents who voted *definitely*, *probably* and *no* are described by the decision variables. Respondents tend to vote *definitely* rather than *probably* or *no* if the respondent; is young; has a cottage in the archipelago; has made a visit to the archipelago during the summer; has a higher income and does not live in Uppsala County.

Table 2. Overall voting behavior

	definitely		*probably*		*no*	
variable	mean	stdv.	mean	stdv.	mean	stdv.
resident	0.083	0.277	0.080	0.271	0.086	0.280
cottage	0.252	0.435	0.194	0.396	0.170	0.376
visit	0.694	0.461	0.622	0.485	0.435	0.496
female	0.541	0.499	0.543	0.498	0.516	0.500
age	44.941	13.510	46.895	14.756	49.198	15.344
income	14 090	8 926	12 606	7 317	11 898	8 113
U. County	0.097	0.296	0.128	0.334	0.160	0.367
N	1 074		913		438	

Before analyzing the data more thoroughly some structural differences have to be addressed. The data were collected at the end of the summers of 1998 and 1999. In 1998, when data for the probabilities 0.5, 0.75 and 0.9 were collected, the temperature was below season average and rainfall above. In 1999, when data for the probabilities 0.1, 0.25 and 0.5 were collected, the summer was characterized by little rainfall and high temperatures.[6] Table A1, (in the Appendix), reveals that there are some structural differences in the data, especially with respect to visit, age and voting behavior. For the year 1998 (low temperature, rainfall, but high probability of reversibility) there are more people who on average vote *no*, there are fewer visits and the average respondent is older.

4.1. Between-sample design. We account for these structural differences by testing the two years apart. Table 3 reports these results.

For the year 1998 we find that the dummies, d75 and d90 are not significant. The variables visit, income, U. County and age are statistically significant, although the marginal effects are small. Visit and income have positive signs, meaning that the probability to vote *definitely* increases with income and is higher for a person who made a visit to the archipelago during the summer. Age and the dummy for a residence in

[6] This observation is based on the average rainfall and temperature (May-September) for the 1998 and 1999 and was obtained from IVL Svenska Miljöinstiutet AB (IVL Swedish Environmental Institute Co.).

Uppsala County have negative signs and are the most influential variables (looking at the marginal effects).

Table 3. Ordered Probit Estimates for 1998 and 1999

	1998			1999		
variable	coeff.	p-value	marg. eff.	coeff.	p-value	marg. eff.
constant	1.117	0.000	0.424	1.001	<0.001	0.398
visit	0.001	0.030	0.000	-0.000	0.382	-0.001
income	0.000	0.000	0.000	0.000	0.013	0.000
U. County	-0.304	0.022	-0.115	-0.154	0.248	-0.614
female	0.009	0.915	0.004	-0.003	0.958	-0.001
age	-0.010	0.029	-0.004	-0.000	0.816	0.000
d10	-	-	-	0.056	0.605	0.022
d25	-	-	-	0.061	0.577	0.024
d75	0.001	0.993	0.000	-	-	-
d90	-0.099	0.357	-0.038	-	-	-
μ	1.1978	0.000		1.2493	0.000	
N	705			663		
$\chi^2(r)$	45.5983	0.000		8.924	0.258	
LRI	0.03			0.000		
Log L	-719.577			-643.558		
voting result						
% *definitely*	38.0			47.1		
% *probably*	42.0			40.7		
% *no*	20.0			12.2		

Also for the year 1999, the reversibility dummies are not significant, in this case d10 and d25. In fact, the chi-two test of the null hypothesis that all slopes are equal to zero cannot be rejected. Note that this is not likely to be an effect of that more respondents vote no in 1999; on the contrary 12 percent vote no this year and 20 percent in 1998.

These results indicate that the degree of reversibility makes no difference for voting behavior. But is this really the case or is there any other circumstance causing this result? We will analyze two potentially influential circumstances: 1) the good is complex and only people familiar with the good give "accurate" answers in the sense that they take the degree of reversibility into account, 2) there is a hypothetical bias in responses which drives the result. We have data on people who made a visit to the archipelago during the summer. This variable can be referred to as an experience variable, meaning that visitors are likely to be more informed about the problems of eutrophication than non-visitors. Visitors might thereby be able to make a "better" judgment. However, Table 4 and 5 show that a separation of respondents into visitors and non-visitors does not introduce any expected sensitivity for the degree of reversibility.

Table 4. Ordered Probit Estimates for 1998 and 1999, visitors

	1998			1999		
variable	coeff.	p-value	marginal eff.	coeff.	p-value	marginal eff.
constant	1.243	0.005	0.493	2.222	0.000	0.855
income	0.000	0.012	0.000	0.000	0.611	0.000
female	-0.157	0.228	-0.062	-0.003	0.973	-0.001
age	-0.005	0.456	-0.002	-0.018	0.000	-0.007
U. County	-0.034	0.891	-0.014	0.085	0.734	0.033
d10	-	-	-	0.125	0.368	0.048
d25	-	-	-	0.105	0.464	0.040
d75	0.057	0.702	0.023	-	-	-
d90	0.036	0.820	0.820	-	-	-
μ	1.364	0.000		1.464	0.000	
N	349			433		
$\chi^2(r)$	10.343	0.111		27.790	0.000	
LRI	0.015			0.036		
Log L	-330.383			-367.452		
voting results						
% definitely	45.8			54.0		
% probably	43.3			39.3		
% no	10.9			6.7		

Table 5. Ordered Probit Estimates for 1998 and 1999, non-visitors

	1998			1999		
variable	coeff.	p-value	marginal eff.	coeff.	p-value	marginal eff.
constant	0.960	0.021	0.340	0.129	0.617	0.046
income	0.000	0.002	0.000	0.000	0.000	0.000
female	0.197	0.116	0.070	0.241	0.129	0.086
age	-0.013	0.051	-0.005	0.002	0.501	0.001
U. County	-0.262	0.115	-0.093	0.112	0.523	0.039
d10	-	-	-	-0.044	0.818	-0.016
d25	-	-	-	0.090	0.620	0.032
d75	-0.075	0.617	-0.023	-	-	-
d90	-0.255	0.094	-0.090	-	-	-
μ	1.100	0.000		1.248	0.000	
N	337			222		
$\chi^2(r)$	23.858	0.000		19.680	0.003	
LRI	0.033			0.042		
Log L	-354.487			-226.501		
voting results						
% definitely	32.0			23.0		
% probably	40.1			44.1		
% no	27.9			23.0		

One approach aiming at reducing hypothetical bias in CVM studies is to collect information about how certain respondents were about their answer to a willingness to pay question (see Champ et al., 1997; Champ and Bishop, 2001; Blumenschein et al., 2004). The fact that our respondents could vote definitely or probably enables us to carry out a similar adjustment of hypothetical bias.

We thus test the consequences of pooling *probably* and *no* answers. This is based on the argument that only those voting definitely would accept the scenario in a real-world situation. This means that the proportion of people voting *no* (*no/probably*) increases from 20% to 62% for 1998, and from 12% to 52% for 1999. However, the estimation results in Table A2 (in the Appendix) show that reversibility remains insignificant.

4.2. Within-sample design. From the results obtained so far one could be tempted to conclude that the degree of reversibility has no effect on voting behavior. However, this result seems to depend crucially on the between-sample design. A completely different picture appears when the data for the within-sample design are analyzed, see Table 6 for estimation results.

Table 6. Random effects ordered probit estimates

variable	coeff.	p-value	marg.eff.
constant	3.270	0.000	1.299
visit	-0.002	0.017	-0.001
income	0.000	0.358	0.000
U. County	-0.563	0.212	-0.224
female	0.167	0.564	0.066
age	-0.019	0.048	-0.008
d10	-2.263	0.000	-0.899
d25	-1.231	0.000	-0.489
d75	1.236	0.000	0.491
d90	1.795	0.000	0.713
μ	2.760	0.000	
σ	2.546	0.000	
N	1055		
$\chi^2(r)$	560.523	0.000	
LRI	0.292		
Log L	-680.067		
voting results			
% definitely	55.0		
% probably	38.8		
% no	6.2		

Reversibility is now strongly significant, both statistically and economically. The dummy variables for the different probabilities of success also have the "right signs", meaning that the probability of voting definitely increase for percentage rates above 50% and decreases for percentage rates below 50%. In addition, the marginal effects of these dummies clearly dominate all other variables that show statistical significance (visit and age).

5. Discussion and concluding remarks

The aim of this paper was to analyze how people respond to a potential irreversibility of environmental degradation. The study was motivated by the empirical observation that many ecosystems have degraded to the point where it is uncertain whether a healthy state can be recovered regardless the amount of resources devoted to the purpose.

Our results are mixed and depend crucially on the referendum design. When each respondent faces only one probability of reversibility in the between-sample design, we find that the degree of uncertainty makes no difference for voting behavior. This result is robust when we account for hypothetical bias. We also tested if respondents more familiar with respect to characteristics of the good voted differently as compared to unfamiliar voters, but found that this was not the case. From these results one could be tempted to conclude that people do not respond to the degree of reversibility.

Insensitivity to scope in CVM studies is often attributed to warm glow motives (Andreoni, 1989, 1990). Such motives exist when a person contributes to a public good because the act of contributing in itself provides some benefit to the individual. However, this cannot be the whole story in our case, because the within-sample design shows that when a respondent faces different probabilities of reversibility, not only is this uncertainty characteristic significant, but also dominates all other decision variables.

It is not clear to us which of the two designs that results in the most correct elicitation of people's preferences. For example it has been argued that there are circumstances where people have problems of interpreting information, here about uncertainty, if no reference point is given (Kahneman et al., 1999). One might also argue that the sensitivity to the degree of reversibility shown in the within-sample design is a methodological artefact in the sense that this design "forces" people to be consistent. The sensitivity might then be due to that people want to appear to be consistent rather than due to actually consistent preferences (Kahneman et al., 1999).

Ariely, Loewenstein and Prelec (2003) conducted a series of experiments where consumers priced simple pains (high pitch noises played over headphones). They found

that pricing was not consistent with fundamental valuation. However, when the same subject priced different durations of the sound, the relative value of the noises of different durations was coherent. Preferences became imprinted after an initial choice and prior to imprinting preferences were arbitrary. They concluded that this behavior was robust against manipulations such as; information and experience about the good, higher stakes, market forces and monetary incentives. They introduced the concept "coherent arbitrariness", which is meant to capture the fact that people respond robustly and sensitively (coherent) to changes in relevant variables such as prices but at the same time, subjects' responses occur around a base-level which is arbitrary.

Our results show a similar tendency and we must conclude that we cannot say who wants to save the Baltic Sea; the answer essentially depends on how we ask. This suggests that more research is needed for understanding how people respond to the type of uncertainty analyzed in this paper.

Appendix

Voting scenario in the questionnaire – between-sample design

The water in the Stockholm Archipelago might be improved if measures are taken against nutrient emission from e.g., agriculture and household sewage. Suppose that an abatement program has been proposed. According to this program, farmers and sewage treatment plants in the counties of Stockholm, Södermanland and Uppsala have to put money into measures against the nutrient emissions. This would in turn result in increased prices of agricultural products and tap water in these counties. The following would also happen:

- Nature is not completely predictable, so there is no guarantee that the proposed abatement program will succeed. Suppose the chance of successful measures would be very high (90 percent)/rather high (75 percent)/fifty-fifty (50 percent)/rather low (25 percent)/very low (10 percent).[7] If the program is successful the measures would improve the water quality in the archipelago.
- For example, the water transparency in the inner and central parts of the archipelago would on average increase from the present average of about 1 meter in summers to about 2 meters in 10 years. As a rule, it would thus in 10 years be possible to discern one's feet on the bottom wherever one bathes in the archipelago. If the program is not successful, the water quality would not be improved, but the ongoing deterioration would continue at a slower rate than before.
- If no measures are taken, the ongoing deterioration would continue at the same rate as today, and the water would gradually become more turbid.

QUESTION. Would you accept or not accept to pay something in terms of increased expenses in order to make it possible to carry out this abatement program?

☐ I WOULD DEFINITELY ACCEPT
☐ I WOULD PROBABLY ACCEPT
☐ I WOULD NOT ACCEPT

[7] The five sub-samples used in the between-sample design only differed with respect to what of the five descriptions of the chance of success was used.

Voting scenario in the questionnaire – within-sample design

The water in the Stockholm Archipelago might be improved if measures are taken against nutrient emission from e.g., agriculture and household sewage. Suppose that an abatement program has been proposed. According to this program, farmers and sewage treatment plants in the counties of Stockholm, Södermanland and Uppsala have to put money into measures against the nutrient emissions. This would in turn result in increased prices of agricultural products and tap water in these counties. The following would also happen:

- Nature is not completely predictable, so there is no guarantee that the proposed abatement program will succeed. **If the program is successful**, the measures would improve the water quality in the archipelago.
- For example, the water transparency in the inner and central parts of the archipelago would on average increase from the present average of about 1 meter in summers to about 2 meters in 10 years. As a rule, it would thus in 10 years be possible to discern one's feet on the bottom wherever one bathes in the archipelago. If the program is not successful, the water quality would not be improved, but the ongoing deterioration would continue at a slower rate than before.
- If no measures are taken, the ongoing deterioration would continue at the same rate as today, and the water would gradually become more turbid.

QUESTION. Would you accept or not accept to pay something in terms of increased expenses in order to make it possible to carry out this abatement program, if...

a) ...the chance of successful measures would be very high (90 percent)?

☐ I WOULD DEFINITELY ACCEPT
☐ I WOULD PROBABLY ACCEPT
☐ I WOULD NOT ACCEPT

b) ...the chance of successful measures would be rather high (75 percent)?

☐ I WOULD DEFINITELY ACCEPT
☐ I WOULD PROBABLY ACCEPT
☐ I WOULD NOT ACCEPT

c) ...the chance of successful measures would be fifty-fifty (50 percent)?

- ☐ I WOULD DEFINITELY ACCEPT
- ☐ I WOULD PROBABLY ACCEPT
- ☐ I WOULD NOT ACCEPT

d) ...the chance of successful measures would be rather low (25 percent)?

- ☐ I WOULD DEFINITELY ACCEPT
- ☐ I WOULD PROBABLY ACCEPT
- ☐ I WOULD NOT ACCEPT

e) ...the chance of successful measures would be very low (10 percent)?

- ☐ I WOULD DEFINITELY ACCEPT
- ☐ I WOULD PROBABLY ACCEPT
- ☐ I WOULD NOT ACCEPT

Table A1. Testing for structural differences, within-sample design excluded

variable	1998 mean (stdv.)	1999 mean (stdv.)	two-sided t-test of diff., p-values
income	12 560 (5 628)	12 945 (7 625)	0.297
age	54.93 (9.80)	43.85 (15.18)	0.000
visit	0.51	0.66	0.000
female	0.56	0.54	0.446
U. County	0.11	0.13	0.204
voting results			0.000
% *definitely*	38.0	47.0	
% *probably*	42.0	41.0	
% *no*	20.0	12.0	
N	706	664	

Table A2 Binary probit estimates for 1998 and 1999, (probably and no pooled)

	1998			1999		
variable	coeff.	p-value	marg. eff	coeff.	p-value	marg. eff
constant	-0.133	0.684	-0.050	-0.168	0.145	-0.067
visit	0.012	0.011	0.000	-0.000	0.338	-0.000
income	0.000	0.000	0.000	0.000	0.095	0.000
U. County	-0.283	0.076	-0.107	-0.172	0.242	-0.068
female	0.033	0.741	0.012	-0.003	0.600	-0.001
age	-0.007	0.152	-0.003	-0.000	0.228	-0.000
d10	-	-	-	0.033	0.788	0.013
d25	-	-	-	-0.026	0.827	-0.010
d75	0.041	0.729	0.016	-	-	-
d90	-0.091	0.449	-0.035	-	-	-
N	705			663		
$\chi^2(r)$	28.279	0.000		7.824	0.348	
LRI	0.030			0.009		
Log L	-454.561			-454.497		
voting results						
% *definitely*	38.2			47.1		
% *no/probably*	61.8			52.9		

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