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The social and ecological determinants of common pool resource sustainability

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ABSTRACT

We study a dynamic common pool resource game in which current resource stock depends on resource extraction in the previous period. Our model shows that for a sufficiently high regrowth rate, there is no commons dilemma: the resource will be preserved indefinitely in equilibrium. Lower growth rates lead to depletion. Laboratory tests of the model indicate that favorable ecological characteristics are necessary but insufficient to encourage effective CPR governance. Before the game, we elicit individual willingness to follow a costly rule. Only the presence of enough rule-followers preserves the resource given favorable ecological conditions.

Introduction

Common pool resource (CPR) management is fraught with incentive issues. The classic statement of the problem highlights the tension between individual and social incentives for maintaining the stock of a renewable resource in the absence of well-defined property rights (Gordon, 1954; Hardin, 1968). When property rights are ill-defined, resources may be depleted because individuals lack incentives for preservation. In her seminal book, Elinor Ostrom (1990) provides vivid accounts of common pool resource management in a variety of communities around the world (Ostrom, 1990). Intriguingly, she observes great diversity in resource governance outcomes: while some communities are able to sustain common resources for hundreds of years, through changes in government, wars and natural disasters, others consistently fail despite many attempts to design the appropriate governance institutions.

To understand the sources of this diversity, Ostrom has proposed that CPRs be understood as “social–ecological systems” in which multiple interacting factors influence successful resource governance (Ostrom, 2009). These can be grouped into two categories: (1) *ecological* characteristics of the resource system, like the speed of re-growth of the resource, and (2) *social* and behavioral factors that influence CPR usage. This paper combines theory and experiment to study this interaction directly in a controlled setting.

We first develop a novel model of a dynamic, multi-player common pool resource game that captures the effects of ecological parameters on resource dynamics. We show that the optimal resource extraction strategy depends on the rate of

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resource regeneration: for a sufficiently high growth rate, groups maintain the resource indefinitely in equilibrium, and this strategy corresponds to the Social Planner's solution of the game. Thus, for a broad range of parameter configurations, stocks of common pool resources will be preserved in equilibrium, and there is no commons dilemma. However, below some threshold growth rate, groups will instead exhaust the resource, while a Social Planner would prefer to preserve the resource indefinitely. The dependence of equilibrium behavior on ecological parameters of the model may help explain the heterogeneity in common pool resource outcomes around the world (Ostrom, 1990, 2010).

Yet, as noted above, all CPR systems are inextricably bound to the social systems in which they are managed and exploited, and thus favorable ecological characteristics may be necessary conditions without being sufficient to ensure successful CPR management. In the field, rule- (and norm) following tendencies have been implicated in studies of successful CPR systems, where groups of rule-abiding individuals are able to sustain CPRs. Communities composed of such types do not overharvest the resource even when monitoring is nearly non-existent and there are huge benefits from overusage. For example, court records from 1 year in the 15th century Spain show that for 25,000 estimated opportunities of water theft, only 200 instances were observed (a minuscule infraction rate of 0.008), despite the fact that monitors could only check each household approximately once a year (Ostrom, 1990). Additional evidence from Tang (1994, p. 229) supports the idea that groups of individuals with a propensity to follow rules are much more successful in sustaining their resources than groups without such propensities.

With this in mind, we extend our basic model to introduce heterogeneous types that vary in their intrinsic concern for adhering to rules and norms (Kimbrough and Vostroknutov, 2013). We call them rule-breakers and rule-followers, and we assume that the latter receive additional utility from adhering to prescriptive social norms. In particular, we assume that rule-followers prefer to follow the Social Planner's solution to the CPR problem. Compared to the case with purely payoff maximizing agents, we show that there are new equilibria in which (1) groups of rule-breakers may deplete a resource that would otherwise be preserved and (2) groups of rule-followers may preserve a resource that would otherwise be depleted.

These findings hint at the importance of assortative matching and the exclusion of rule-breakers to the successful management of CPRs, but in field studies it is difficult to distinguish successful CPR management due to groups composed of rule-following types from successes due to ecological factors. Thus, we turn to a laboratory experiment in which we aim to measure and control the type-composition of each CPR system.

Our design employs the method developed in KV who classify rule-breaking and rule-following types using an *unrelated* individual decision task in which subjects are asked to follow a *costly rule*. According to their model, which builds on Kessler and Leider (2012), costly rule-following reveals a disutility of violating social norms.[1] Those who incur larger disutilities of violation will be more inclined to follow norms. In a CPR context, the clear social norm is to preserve the resource, though this norm may be in conflict with individual incentives to maximize payoffs. As we show in the model, those who care more about norms will be more willing to trade off own monetary payoffs in order to preserve the resource, but unless norm-insensitive (rule-breaking) types are screened out, such cooperative tendencies may fail.

In two treatments with different CPR growth rates, we classify our subjects as either rule-followers or rule-breakers as described above. In some sessions, unbeknownst to subjects, we sort them into rule-following and rule-breaking groups before observing their behavior in our CPR games, and we test the hypothesis that assortatively matched rule-followers will be more inclined to preserve the CPR than both rule-breakers and mixed-type groups.

While we find that a low resource growth rate always leads to resource depletion (consistent with the baseline SPNE), it generally happens more slowly than predicted. The adapted model with social norms can explain these observations because rule-following individuals tend to restrain their harvesting in attempts to preserve the resource. Moreover, a higher resource growth rate does not always yield sustainability either, though there is a clear difference between groups of rule-followers on one hand and groups of rule-breakers and mixed-type groups on the other hand. Specifically, 45% of our assortatively matched rule-following groups preserve the resource for the entire experiment, while only 18% of the assortatively matched rule-breaking groups and 17% of our mixed-type groups do the same. Consistent with the findings in KV, the presence of rule-breakers leads to cooperation failure because rule-breakers do not try to preserve the resource when it nears depletion.

Ultimately, our results reinforce the intimate relationship between ecological and social factors in preserving CPRs. When the resource growth rate is high, the presence of rule-followers is still necessary to preserve the resource, though the demands on the strength of rule-following preferences are not particularly high. When instead, the resource growth rate is low, only groups composed completely of strong rule-followers can preserve the resource. Thus, while favorable ecological conditions are *necessary* for CPR sustainability, they are not *sufficient* in our behavioral experiments.

The common pool resource game

In this section we present a formal model of the dynamic Common Pool Resource game to highlight how the equilibrium resource extraction strategy depends on ecological parameters. In each period, n players simultaneously allocate productive

[1] Following KV, Kessler and Leider (2012) and Krupka and Weber (2013), and others, we define the social norm in a given setting as the strategy that most individuals (implicitly or explicitly) agree is the most ‘socially appropriate’. While Krupka and Weber (2013) elicit norms experimentally, we do not think it is objectionable to assume that individuals would agree that the socially appropriate action is to maintain the CPR.

efforts between a private, inexhaustible outside option and an exhaustible common pool resource that yields larger per-unit returns to effort. After the effort decisions the resource stock is depleted by an amount equal to the sum of efforts and then regrows at some rate β, proportional to the deviation from total CPR capacity $\overline{w}$. The regrown stock of the resource is then available for the players in the next period. Thus, we have a repeated game with a *state variable*. An additional assumption we make is that the resource ceases to regenerate if the total stock falls below some threshold level τ. Thus, players face a trade-off between depleting the resource today to maximize current consumption and leaving nothing for the future *and* restraining themselves and allowing the resource to regrow, thus providing utility in all periods. We show that the SPNE of this game depends on the *ecological* parameters of the CPR system β and τ. In particular, for high growth rates of β (relative to n and τ) the players sustain the resource indefinitely in equilibrium. For low growth rates the resource is rapidly depleted in equilibrium. The same is true for high (low) τ: the resource is depleted (sustained) in equilibrium. We also study the Social Planner's problem and show that social optimum is to maintain the resource indefinitely *regardless* of the values of β and τ.

The dependency of the equilibrium on the parameters allows us to test whether and how different ecologies influence behavior in the experiments, particularly because the predictions are sharply different for different parameterizations (sustainability vs. depletion). Moreover, we can investigate how observed behavior relates to the social optimum, which is especially interesting in the case where the SPNE and the solution to the Social Planner's problem are polar opposites. The next sections describe the NE and SPNE of one-shot stage game and the dynamic game as well as the Social Planner's solution.

One-shot game

Suppose there is a common pool resource with initial stock $w>0$. There are n players who simultaneously choose how much effort to exert in harvesting the resource. Each player i chooses effort $e_i \in [0,\overline{e}]$ where $\overline{e}>0$ is a common maximum effort level that can be exerted by each player (e.g. hours worked per day with constant productivity). Let $E=\sum_{i=1..n} e_i$ denote the sum of all efforts. The payoff function for player i is

$$\pi_i(e_i, e_{-i}|w) = \begin{cases} \overline{e} - e_i + \alpha e_i & \text{if } E < w, \\ \overline{e} - p_i(e_i, e_{-i}) + \alpha p_i(e_i, e_{-i}) & \text{if } E \geq w. \end{cases} \tag{1}$$

The intuition behind π_i is the following. For simplicity we assume that the amount of the resource, efforts, and players' utilities are all denominated in the same units. If the sum of all efforts E does not exceed the available amount of the resource w then each player i receives a return on effort equal to αe_i, where $\alpha>1$ ensures that players find it worthwhile to exert effort harvesting the resource. The payoff in this case is $\overline{e}-e_i$, the amount of effort *not spent*, plus αe_i, the return from exerted effort, or $\overline{e}+(\alpha-1)e_i$. If, however, the sum of harvesting efforts exceeds the resource stock, then each player harvests the amount $p_i(e_i, e_{-i})$. This quantity is calculated according to a simultaneous eating algorithm: suppose the players start harvesting the resource simultaneously at the same speed. Each player continues harvesting until either she has exerted the chosen effort or the resource is exhausted. Here players who choose low efforts e_i will receive αe_i if the resource is not fully depleted, and only those who choose high effort end up sharing the remains.[2] This finalizes the description of the stage game. Hereafter, we will call any such game, parameterized by w, a w-game.

Proposition 1. *If $w>n\overline{e}$ then the unique pure strategy Nash Equilibrium of the w-game is $e_i=\overline{e}$ for all $i=1..n$. If $w\leq n\overline{e}$ then any vector $(e_i)_{i=1..n}$ with $e_i \geq \frac{w}{n}$ for all i is a pure Nash Equilibrium of w-game.*

Proof. See Appendix B.

Dynamic game

Next, we analyze the dynamic w-game. Suppose that players make simultaneous effort decisions in L consecutive periods. In each period they may choose to exert effort e_i up to the maximum effort $\overline{e}$. Moreover, the resource stock in future periods depends on the amount remaining after harvesting decisions made in the current period. We assume that the resource naturally grows at a rate inversely proportional to its current size. Furthermore, assume that due to exogenous environmental or technical factors, there exists a maximum resource capacity $\overline{w}$. Now, suppose that after harvesting in period $t-1$ the remaining resource stock is w^*_{t-1}. Then, the stock available before period t is $w^*_{t-1}+\beta(\overline{w}-w^*_{t-1})\mathbb{1}_{w^*_{t-1}\geq\tau}$. Here $0<\beta<1$ is the growth rate and $\mathbb{1}_{w^*_{t-1}\geq\tau}$ equals 1 whenever $w^*_{t-1}\geq\tau$ and 0 otherwise. The interpretation is the following. The more depleted the resource w^*_{t-1}, the faster the resource is able to regenerate. The growth rate approaches 0 as the resource stock approaches $\overline{w}$. However, if the resource is depleted below some level $\tau \ll \overline{e}$, then the resource is exhausted and no regrowth happens thereafter.

Now we can define the dynamic w-game. Denote by $E_t=\sum_{i=1..n} e_{it}$ the sum of efforts of all players in period $t=1..L$. Suppose that *before* period 1 the stock of the resource is w_1. In period 1 players choose effort levels that determine E_1 and, consequently, the resource stock decreases to $w^*_1=(w_1-E_1)\mathbb{1}_{w_1-E_1>0}$. This is the amount of the resource left *after* period 1.

[2] See Appendix A for the formal description of the algorithm.

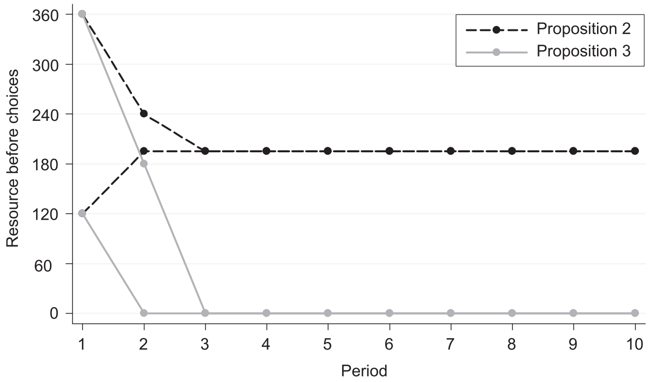

Fig. 1. Possible equilibrium paths for parameter assumptions in Propositions 2 and 3. We display the paths for two different initial resource stocks w_1: 360 and 120. The growth rates (β) depicted here are exactly those from the experimental CPRL (0.25) and CPRH (0.50) treatments (see Experimental design section).

Then the resource regrows, and the stock becomes $w_2 = w_1^* + \beta(\overline{w} - w_1^*)\mathbb{1}_{w_1^* \geq \tau}$, which is the amount available at the beginning of period 2. At this moment period 2 begins. Defining the same quantities for all periods we get the resource stock available *before* period $t > 1$ to be

$$w_t = w_{t-1}^* + \beta(\overline{w} - w_{t-1}^*)\mathbb{1}_{w_{t-1}^* \geq \tau} \tag{2}$$

where $w_t^* = (w_t - E_t)\mathbb{1}_{w_t - E_t > 0}$.

Let H_t denote the set of all histories of effort choices in periods 1 through t. The typical element of H_t is $h_t = ((e_{i1})_{i=1..n}, \ldots, (e_{it})_{i=1..n})$. The history of choices h_t defines the sequence $(E_k(h_t))_{k=1..t}$ of sums of efforts. Here $E_k(h_t)$ denotes the sum of efforts in period k as defined by h_t. This sequence in turn generates the sequence of resource stocks $(w_k(h_t))_{k=1..t}$ available *before* periods k as determined by the recursive application of the resource growth formula above. The stage game played in period $t+1$ after history h_t is $(w_t^* + \beta(\overline{w} - w_t^*)\mathbb{1}_{w_t^* \geq \tau})$-game. The utility of player i after terminal history h_L is then defined by

$$\sum_{k=1}^{L} \pi_i(e_{it}, e_{-it} | w_k(h_L)).$$

This completely defines the (history-dependent) repeated CPR game.

Now we turn to the equilibrium analysis of the dynamic CPR game. The following proposition shows that there exists a symmetric Markov Subgame Perfect Nash Equilibrium in which players exert maximum effort $\overline{e}$ in any period in which doing so will not deplete the resource below τ. When the resource stock in period t is $w_t < n\overline{e} + \tau$ the equilibrium strategy is for all players to exert effort so that the resource is depleted to exactly τ. Thus, the resource will be preserved indefinitely in equilibrium.

Proposition 2. *If $\beta \geq \frac{\tau(n-1)}{\overline{w} - \tau}$ and $\tau \leq \overline{e}$ then the following strategy used by all players constitutes a SPNE. In periods $t = 1..L$ choose $e_{it} = \overline{e}$ if the resource before period t is $w_t \geq n\overline{e} + \tau$. In period $t = 1..L-1$ choose $e_{it} = \frac{w_t - \tau}{n}$ if $w_t \in [\tau, n\overline{e} + \tau)$ and $e_{it} = \frac{w_t}{n}$ if $w_t < \tau$. Choose $e_{iL} = \min\{\overline{e}, \frac{w_L}{n}\}$ if $w_L < n\overline{e} + \tau$.*

Proof. See Appendix B.

Proposition 2 implies the following behavior along the equilibrium path, given parameter values:

Implication 1. If $\beta \geq \frac{n\overline{e}}{\overline{w} - \tau}$ then the strategy stated in Proposition 2 is a SPNE if used by all players. Moreover, if $w_1 \geq n\overline{e} + \tau$ then on the equilibrium path all players will exert effort $\overline{e}$ in all periods. If $w_1 \in [\tau, n\overline{e} + \tau)$ players will exert effort $\overline{e}$ in all periods but the first, where they will put effort $\frac{w_1 - \tau}{n}$. If $w_1 < \tau$ then in period 1 all players will exert effort $\frac{w_1}{n}$ and 0 effort in the remaining periods.

Implication 2. If $\beta < \frac{n\overline{e}}{\overline{w} - \tau}$ then the strategy stated in Proposition 2 is a SPNE if used by all players. Moreover, if $w_1 \in [\tau, n\overline{e} + \tau)$ players will exert effort $\frac{w_1 - \tau}{n}$ in period 1; efforts $\frac{\beta(\overline{w} - \tau)}{n}$ in periods 2 to $L-1$ and effort $\min\left\{\overline{e}, \frac{\tau + \beta(\overline{w} - \tau)}{n}\right\}$ in period L. If $w_1 \geq n\overline{e} + \tau$ and $L < M$ then on the equilibrium path all players will exert effort $\overline{e}$ in all periods (see Lemma 1 for the value of M). If $w_1 \geq n\overline{e} + \tau$ and $L \geq M$ then on the equilibrium path all players will exert effort $\overline{e}$ in periods 1 to $M-1$ and efforts like in case $w_1 \in [\tau, n\overline{e} + \tau)$ afterwards. If $w_1 < \tau$ then in period 1 all players will exert effort $\frac{w_1}{n}$ and 0 effort in the remaining periods.

The SPNE constructed above holds for relatively low values of $\tau (\tau \leq \overline{e})$ and/or relatively high levels of $\beta (\beta \geq \tau(n-1)/(\overline{w} - \tau))$ because in these cases the temptation to exert high effort, so that the resource is depleted below τ, is overcome by the high resource growth resulting from exerting less effort today. However, if β is low, then this trade-off disappears and the only SPNE is for all players to exert the highest possible symmetric effort. The following proposition describes the result.

Proposition 3. *If $\beta \le \frac{\tau(n-1)}{\overline{w}-\tau}$, $\beta > \frac{n\tau}{\overline{e}} - n + 1$ and $\beta \le \frac{(2n-1)\overline{e}-\overline{w}}{(n-1)\overline{e}}$ then the following strategy used by all players constitutes a SPNE. In period $t = 1..L-1$ choose $e_{it} = \overline{e}$ if the resource before period t is $w_t \ge n\overline{e}+\tau$. In period $t = 1..L-1$ choose $e_{it} = \frac{w_t - \tau}{n}$ if $w_t \in \left(n\overline{e}+\tau-\frac{\beta(\overline{w}-\tau)}{n-1}, n\overline{e}+\tau\right)$. In period $t = 1..L-1$ choose $e_{it} = \min\{\overline{e}, \frac{w_t}{n}\}$ if $w_t \le n\overline{e}+\tau-\frac{\beta(\overline{w}-\tau)}{n-1}$. Choose $e_{iL} = \min\{\overline{e}, \frac{w_L}{n}\}$ for all w_L.*

Proof. See Appendix B.

The following describes behavior along the equilibrium path under the strategy detailed in Proposition 3.

Implication 3. If $\beta \le \frac{\tau(n-1)}{\overline{w}-\tau}$, $\beta > \frac{n\tau}{\overline{e}} - n + 1$ and $\beta \le \frac{(2n-1)\overline{e}-\overline{w}}{(n-1)\overline{e}}$ then the strategy stated in Proposition 3 is a SPNE if played by all players. On the equilibrium path players harvest $\overline{e}$ if the resource is higher than $n\overline{e}$ and harvest $1/n$ fraction of the resource otherwise.

Fig. 1 shows equilibrium paths for different initial conditions and different parameter combinations (as in the two propositions above). It can be easily seen that for the assumptions of Proposition 2 the resource stock converges to the level $\tau+\beta(\overline{w}-\tau)$ and for the assumptions of Proposition 3 the resource stock converges to 0.

An important observation about Propositions 2 and 3 should be made. In the interesting case $\overline{w}-\frac{1-\beta}{\beta}n\overline{e} < n\overline{e}$, where even with high w_1, exerting efforts $\overline{e}$ eventually depletes the resource to a level less than $n\overline{e}$ (where depletion is possible), for any given parameters only one of the two SPNE described in the propositions above can occur (unless $\beta = \frac{\tau(n-1)}{\overline{w}-\tau}$, where there are two SPNE). This is clear from the proofs of Case 2.1 of Proposition 2 and the second case of Proposition 3: the restrictions on β ($\beta \ge \frac{\tau(n-1)}{\overline{w}-\tau}$ and $\beta \le \frac{\tau(n-1)}{\overline{w}-\tau}$ correspondingly) are equivalent to the no profitable deviation conditions. Therefore, our model predicts the existence of either one or the other symmetric Markov SPNE for any set of parameters.

In sum, while in some cases, our model predicts overharvesting of CPRs in line with the classic statement of the commons problem, we also find that in equilibrium for a range of parameters, there is no commons dilemma. For a sufficient growth rate, CPRs can be sustained indefinitely.[3]

Social planner's problem

In this section we consider the same problem from the perspective of a Social Planner who seeks to maximize the sum of individual utilities in our CPR game. Without loss of generality we will solve for the optimal harvesting strategy in the single player case. In each period t, the Social Planner's payoff is defined by the first part of Eq. (1)

$$\pi(e_t|w_t) = \overline{e} + (\alpha-1)e_t \quad \text{where } 0 \le e_t \le \min\{\overline{e}, w_t\}.$$

In what follows we will abuse notation and assume that $\pi(e_t|w_t) = e_t$ without loss of generality.

Given the initial resource stock w_1, a Social Planner faces the following problem:

$$\max_{(e_t)_{t=1..L}} \sum_{t=1}^{L} e_t \tag{3}$$

$$\text{s.t.} \quad w_{t+1} = w_t - e_t + \beta(\overline{w} - (w_t - e_t))\mathbb{1}_{w_t - e_t \ge \tau}$$
$$0 \le e_t \le \min\{\overline{e}, w_t\}.$$

Before proceeding to the proposition describing the solution to this problem, let us first make a useful observation. By Lemma 2, no solution to the above problem can have $w_t < \tau$ for $t = 1..L-1$. Thus, we can simplify the problem by removing the (never optimal) choices that lead to the case $w_t < \tau$

$$\begin{aligned}
&\max_{(e_t)_{t=1..L}} \sum_{t=1}^{L} e_t \\
&\text{s.t.} \quad w_{t+1} = w_t - e_t + \beta(\overline{w} - (w_t - e_t)) = (1-\beta)(w_t - e_t) + \beta\overline{w} \\
&\qquad 0 \le e_t \le \min\{\overline{e}, w_t - \tau\} \text{ for } t = 1..L-1 \\
&\qquad 0 \le e_L \le \min\{\overline{e}, w_L\}.
\end{aligned} \tag{4}$$

The solution to problem (4) must be the same as to problem (3).

Now we are ready to find the solution.

[3] We would like to emphasize that the equilibria in Propositions 2 and 3 are constructed so that the second part of the one period utility Definition 1 is never used. Namely, no player ever exerts effort that makes the sum of efforts bigger than the available resource. Therefore, the result of these propositions does not depend on the particulars of the mechanism that is used to split the resource in this case. However, given the simultaneous eating algorithm that we use in our experiment, there are other possibilities available. In particular, when the resource can be exhausted and there are incentives to exhaust it, the players might choose maximal effort instead of trying to exactly exhaust it to zero by choosing $1/n$th of what is available. In this case it would be harder to sustain cooperation, since a player must sacrifice more payoff in order to keep the resource at level τ to continue growth. This possibility will be considered in detail in the model with norms in Model with norms section.

Proposition 4. *The following choice procedure generates the solution to the Social Planner's problem (3) as long as $\tau < \overline{e}$. In periods $t = 1..L, e_t = \overline{e}$ if the resource before period t is $w_t \geq \overline{e} + \tau$. However, in period $t = 1..L-1, e_t = w_t - \tau$ if $w_t \in [\tau, \overline{e} + \tau)$ and $e_t = w_t$ if $w_t < \tau$. If $w_L < \overline{e} + \tau$ then $e_L = \min\{\overline{e}, w_L\}$.*

Proof. See Appendix B.

The following summarizes optimal behavior of the planner.

Implication 4. For any combination of parameters, the Social Planner will sustain the resource indefinitely. In every period, the Planner either harvests the maximum possible quantity $\overline{e}$ or harvests to exactly τ, ensuring that the resource is not depleted.

The solution to the Social Planner's problem is to sustain the resource indefinitely for any combination of parameters. Note that the Social Planner's optimal plan precisely mimics the strategies of players in the SPNE of the game with a high resource regrowth rate as described in Proposition 2 for *all* combinations of parameters. However, with a low regrowth rate, the planner would prefer to sustain the resource while individuals rapidly deplete it in equilibrium.[4] Thus, for low growth rate CPR systems, this finding highlights the tension at the heart of the commons problem and provides an additional benchmark against which to compare behavior.

Model with norms

In this section we introduce a modification of the dynamic game from Dynamic game section in which some players have an additional preference for following the "norm," which is described by the Social Planner's solution. This is a variant of the modeling strategy employed in KV. This game will provide the intuition for our experimental results described below. We should notice, also, that we consider only the extension for the parameters that we use in the experiments. The general setup is too cumbersome to present here and might be a topic for a separate paper. We also consider only two types, rather than a continuum, because this is sufficient to generate the intuition we wish to provide.

Suppose that the game is as in Dynamic game section, but with one modification. There are two types of players: rule-followers and rule-breakers. Rule-followers have a slightly modified utility function. In particular, in any information set, a rule-follower receives additional utility $u > 0$ if she chooses the action prescribed by the solution to the Social Planner's problem as described in Proposition 4, i.e. $1/n$ th of the effort that would be chosen by a unitary planner (Cárdenas, 2011). Rule-breakers maximize material payoffs as above, but with one modification. We assume that rule-breakers make full use of the simultaneous eating algorithm in their utility function. In particular, they exert full effort whenever it is (weakly) in their interest to do so, even if this choice will make the sum of efforts higher than the amount of resource available.[5] Rule-followers' and rule-breakers' utility is different in only one respect: for some actions of the rule-followers, an additional constant utility u is added.

Formally, rule-follower's utility in a period is

$$\pi'_i(_i, e_{-i}|w) = \begin{cases} \overline{e} - e_i + \alpha e_i + \mathbb{1}_{e_i = \overline{e}} u & \text{if} w \geq n\overline{e} + \tau \\ \overline{e} - e_i + \alpha e_i + \mathbb{1}_{e_i = (w-\tau)/n} u & \text{if} w \in [\tau, n\overline{e} + \tau) \\ \overline{e} - e_i + \alpha e_i + \mathbb{1}_{e_i = w/n} u & \text{if } w < \tau \end{cases} \quad (5)$$

if the sum of efforts is below w and

$$\pi'_i(_i, e_{-i}|w) = \begin{cases} \overline{e} - p_i(e_i, e_{-i}) + \alpha p_i(e_i, e_{-i}) + \mathbb{1}_{e_i = (w-\tau)/n} u & \text{if } w \in [\tau, n\overline{e}) \\ \overline{e} - p_i(e_i, e_{-i}) + \alpha p_i(e_i, e_{-i}) + \mathbb{1}_{e_i = w/n} u & \text{if } w < \tau \end{cases}. \quad (6)$$

if the sum of efforts is above w. Here $\mathbb{1}_{e_i = x}$ is a function equal to 1 when $e_i = x$ and 0 otherwise. The game for rule-followers is exactly the same in all other respects as in the model without norms. Rule-breakers have the utility without norms as in the model in the previous sections.

We want to see what sort of equilibria this model has for different mixtures of rule-followers and rule-breakers. We will consider the parameters of the model from our experiment (detailed below): $\overline{w} = 360, \overline{e} = 60, n = 4; \beta_H = 0.5, \beta_L = 0.25,$

[4] One caveat is that, for the planner's solution to correspond in this way, we must assume the absence of externalities associated with extraction of the resource. If, for example, some members of society are not involved in resource extraction but value the resource stock for other reasons, then the Social Planner's solution will *not* correspond to the SPNE of the high-growth game. Suppose that the resource is a forest in which some members of society enjoy hiking. In Appendix D we find the solution to the Social Planner's problem with a negative externality of extraction. We assume that there is some level of the resource $\eta > \tau$ such that if the resource is above that level then some additional utility u is enjoyed by the society. Proposition 6 in Appendix D shows that in this case the optimal solution is to deplete the resource to some level above τ so that the resource grows between periods to exactly η. It is important to notice that this is true for *all* possible growth rates of the resource.

[5] See related discussion in the last paragraph of Dynamic game section. We make this assumption for several reasons. First we want to make the model as similar as possible to our experimental setup. Since under the simultaneous eating algorithm, exerting full effort when the resource can be fully exhausted is costless, it is reasonable that this strategy would be attractive to subjects (and indeed it is: Figure F3 shows that many rule-breakers choose full effort right before the exhaustion of the resource). Second, this strategy helps to demonstrate our intuition on why the resource gets exhausted in high growth rate treatment.

Table 1
SPNE in models with high and low growth rates and different numbers of rule-breakers. The u rows show the minimal utility that should be enjoyed by the rule-followers in order for them to optimally choose the Social Planner's solution.

	Number of rule-breakers				
β/u	4	3	2	1	0
β_H	exh	sus	sus	sus	sus
u^*		0	0	0	0
β_L	exh	exh	exh	sus	sus
u^*		20	30	67.5	67.5

exh, the resource is exhausted in SPNE; sus, the resource is sustained in SPNE.

$\tau = 30, \alpha = 2, L = 10$. Notice that we have two treatments, one with a high growth rate (β_H) and one with a low growth rate (β_L). The rest of the parameters is held constant. High β represents the case of Proposition 2 and low β of Proposition 3.

The following proposition characterizes the SPNE for the cases with different combinations of rule-followers and rule-breakers.

Proposition 5. *As the number of rule-breakers declines, the resource is more easily sustained. 4 rule-breakers: In the SPNE each player chooses $\overline{e}$ for all levels of the resource in all periods except the interval* $[215, 270]$, *in which players choose $\frac{w-\tau}{n}$. This is true for both β_L and β_H. 3 rule-breakers: In the SPNE the single rule-follower follows the solution to the Social Planner's problem. He exerts effort $\overline{e}$ for resource levels above 270 (i.e. $n\overline{e}+\tau$), effort $\frac{w-\tau}{n}$ for $w \in [30, 270)$ and effort w/n for $w < 30$. This can only be sustained as an equilibrium strategy when $u \geq 20$. Rule-breakers follow a strategy similar to that above, varying only the thresholds; they exert effort $\frac{w-\tau}{n}$ in the interval* $[190, 270]$ *for β_H and* $[228.75, 270]$ *for β_L.*

2 *rule-breakers*: The same strategies as in the previous case constitute the SPNE. The equilibrium can be sustained only if $u \geq 30$. The intervals in which rule-breakers choose not to exert full effort are $[150, 270]$ for β_H and $[187.5, 270]$ for β_L.

1 rule-breaker: The same strategies constitute SPNE as long as $u \geq 67.5$. The intervals in which the single rule-breaker chooses $\frac{w-\tau}{n}$ instead of $\overline{e}$ is $[30, 270]$ for both β_H and β_L.

0 rule-breakers: Rule-followers follow the same strategy as above. This can be sustained only for $u \geq 67.5$. This holds for both β_H and β_L.

Proof. See Appendix E.

Table 1 summarizes the types of equilibrium that can be sustained with different combinations of rule-followers and rule-breakers. In the model with high growth rate the presence of 4 rule-breakers exhausts the resource though the equilibrium with exhaustion cannot be sustained if there are fewer rule-breakers. In the model with a low growth rate, the resource is exhausted with 4, 3 or 2 rule-breakers and is sustained with 1 or no rule-breakers. In all equilibria, the rule-followers choose the Social Planner's solution in all information sets, the rule-breakers choose to fully exhaust the resource whenever possible in the equilibria where the resource is exhausted and to preserve it in the equilibria where the resource is sustained. For proofs, see Appendix E. The table also shows the values of u^*, the rule-following utility necessary to induce players to follow the Social Planner's solution under each growth rate we study. This shows how ecological and social factors interact in our model: in the low growth environments only relatively strong rule-followers will be able to sustain the resource; in the high growth environments any marginal positive utility from rule-following will induce cooperation.

These equilibria suggest that (1) the resource can be exhausted even with high growth rate if there are many rule-breakers in the group; (2) even when growth rate is low, the resource can be sustained if there are many rule-followers in the group. In reality the players do not know the types of others; therefore, a model with incomplete information would be more realistic. It is straightforward but tedious to analyze this model, and it does not provide much additional insight into the problem. Thus we do not provide it in this paper. However, it is not hard to see that in such model the behavior of rule-breakers and rule-followers (to choose $\overline{e}$ or to try to maintain the resource) will depend on their *beliefs* about the number of rule-breakers in the group. If they believe that there are many rule-breakers, the resource will be exhausted. If they believe that there are very few rule-breakers, the resource might be sustained. In CPRH treatment and CPRL treatment sections we provide evidence that our data fits this intuition very well. The following describes the behavioral implications of heterogeneous types in the CPR game.

Implication 5. When some agents care about norms, it becomes harder to sustain the resource the more rule-breakers there are in the group and the lower is the growth rate. Moreover, in the low growth rate environment the rule-following proclivities of the players should be strong in order to sustain the resource. In the high growth environments the adherence to the norms does not need to be very strong to sustain the resource.

Comparison to other CPR models

Our model differs from the classical common pool resource games reported in previous literature (Gardner et al., 1990; Walker et al., 1990; Walker and Gardner, 1992; Ostrom et al., 1994b; Falk et al., 2002; Velez et al., 2009). In the classical repeated CPR game, the stage game payoff is defined by $\pi_i = e - x_i + (x_i / \sum x_i) F(\sum x_i)$, where F is a strictly concave function with a maximum and x_i is the amount extracted by player i. This models a situation in which each person's resource extraction imposes a direct negative externality on others if the total extraction level exceeds certain amount (when F decreases in x_i). With this payoff function in the unique symmetric Nash equilibrium, more of the CPR is extracted than in the social optimum, thus creating a negative externality. Moreover, in the NE the resource is not depleted (Walker and Gardner, 1992). A payoff function of this type is usually used in *one-shot* CPR games, in order to "approximate" the intrinsically dynamic nature of the CPR process. This is the reason why F needs to have a maximum (Dasgupta and Heal, 1980). In our *dynamic* setting, the stage game payoff obtains if $F(x) = \alpha x$. Thus, F is strictly increasing everywhere. Nevertheless, this does not mean that our model does not incorporate a negative externality that players impose on others when extracting a lot of resources. In our setting players negatively affect others *in the next period*, since the common stock decreases for everyone after a large extraction, leaving others with less resources to extract in the future. Therefore, in our dynamic setting there is no need to use the bell shaped production function. Indeed, our *inter-period* resource growth function defined in (2) satisfies the original concavity assumptions made in Dasgupta and Heal (1980, Diagram 3.1).

Another implication of our modeling choice is that our one-shot CPR game has NE in which all players choose to extract the maximum possible amount of the resource (as compared to the classical game, where this is not the case). In modeling dynamic interactions of players, we find this property desirable for two reasons. First, it is intuitive that if players are in the last period of the dynamic game, they would be willing to extract as much of the resource as they can in order to maximize their utility. Second, Proposition 2 shows that for some parameters the resource is *not* depleted in the SPNE of the dynamic game. This result would be less salient if the stage game had a NE in which players do not extract the maximum amount possible. This shows that the very dynamic nature of CPR systems might help account for the observation that many CPRs are sustainably harvested outside the lab (Ostrom et al., 1992).

However, not every dynamic CPR game has this property. For example, in the classical CPR literature only repeated games are considered, i.e. the stage game in each period is *the same*. As is well known from standard game theoretic arguments, if there is a unique NE of the stage game, then finite repetition of this game has a unique SPNE which corresponds to playing the unique NE in each node. Therefore, the sustainability of the resource in the SPNE in our setting is due to the fact that periods are connected through *a state variable*, the remaining stock. Moreover, we find our setup much more realistic since it is not clear why the stock would revert to the same fixed level after each harvest as it does in a repeated CPR game.

There are other dynamic models in the literature. For example, Bru et al. (2003) also consider a CPR game where the resource stock in each period depends on the extraction decisions in previous periods. However, their setup is also more restrictive: 2 players move sequentially and can only choose between high or low extraction rates. In our model the decisions of n players in each period are simultaneous, which may be more realistic for certain types of CPR,[6] and the amount extracted can be any real number. It should be noted though that qualitatively the model in Bru et al. (2003) has similar predictions to our model: in equilibrium the resource is either depleted or is sustained depending on ecological parameters.

Another study is Janssen et al. (2013). The authors study a dynamic CPR game similar to ours: players can extract from a common resource which depletes it, and then the resource replenishes (at a linear rate) before the next period. It is hard to say what the equilibrium predictions of this model are and how these predictions depend on the parameters since the authors do not provide a formal game theoretic analysis of the model. In yet another paper Fischer et al. (2004) analyze an inter-generational CPR game. In their setup the stock also changes each period depending on the extraction decisions in the previous period. However, in their model each player lives for only one period, so, while the resource stock is dynamic, the game itself is not. Instead, they model a sequence of one-shot games with different initial conditions. It is hard to compare this game to our setting since there is no optimization over the dynamic path of extraction choices. It is also worth mentioning the rather different approaches to modeling dynamic changes in the CPR stock taken by Sethi and Somanathan (1996) and Oses-Eraso and Viladrich-Grau (2007). The stock in their evolutionary models evolves continuously depending on the extraction choices of two groups of heterogeneous players. They use replicator dynamics to show how evolutionary stable equilibria without full depletion of the resource can obtain. Qualitatively the differential equation that describes stock dynamics has similar properties to our discrete time dynamics. However, the models are difficult to compare otherwise.

There are models of CPR which relate to our model with norms. Falk et al. (2002) analyze behavior in the standard repeated CPR game when players are inequity averse (Fehr and Schmidt, 1999). They find that so long as there are enough players who dislike advantageous inequality more than disadvantageous inequality and the latter is high enough, there are equilibria in which inequity averse players extract less resource than the amount predicted under the standard NE without social preferences. Our results are similar in that our model also makes predictions about the sustainability of the resource depending on the number of rule-followers and rule-breakers. The utility used in Cárdenas (2011) is the closest to our setup. He looks at the repeated CPR game where government officials can potentially fine the players who extract too much of the resource. In this respect, his utility specification gives the same incentives to restrain resource extraction as the utility we assume for rule-followers.

[6] For example, when fishermen decide how much fish to catch they do not know the decisions of other fishermen who are at sea at the same time.

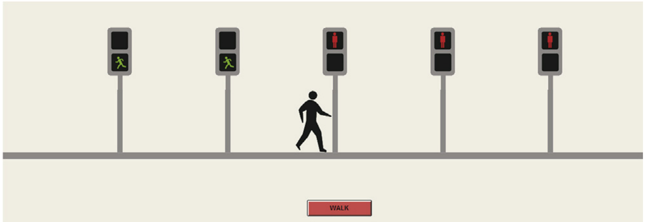

Fig. 2. Screen shot of the Rule Following stage. (a) CPRH . and , (b) CPRL..

Experimental design

Our treatments allow us to test the predictions of our model in the lab and to explore the impact of group type-composition on CPR sustainability. Each session consists of two decision-making stages, followed by a questionnaire, and the following sections describe these stages in detail.

Rule following task

In stage 1, drawn from KV, which we call the Rule Following stage (RF), subjects control a stick figure walking across the computer screen. Each subject makes 5 decisions concerning the amount of time they wait at a sequence of red traffic lights, each of which will turn green 5 s after their arrival. Fig. 2 shows the screen that the subjects see.

The following description of the RF stage closely follows that in KV. At the beginning of the RF stage, the stick figure is standing at the left border of the screen, and all traffic lights are red. Before starting the task, subjects see a short cartoon in which the traffic lights blink from red to green to ensure they understand that the lights can turn green. Subjects initiate the RF stage by pressing the START button. At this moment, the stick figure starts walking towards the first traffic light. Upon reaching the first red light, the stick figure automatically stops. The light turns green 5 s after the stick figure stops; however, subjects are free to press a button labeled WALK any time after the stick figure stops. When a subject presses WALK, the stick figure continues walking to the next red light before stopping again, and subjects must once again press WALK to continue to the next light. Throughout the RF stage, the WALK button is shown in the middle of the screen. Subjects can press the WALK button at any time during the RF stage. However, it becomes functional only when the stick figure stops at a traffic light.

Subjects receive an endowment of 8 Euro, and they are told that for each second they spend in the RF stage they will lose 0.08 Euro. It takes 4 s to walk between each traffic light, and 4 s from the final light to the finish. Therefore, all subjects lose around 2 Euro walking, and if a subject waits for green at all 5 traffic lights, she will lose an additional 2 Euro waiting. Thus the most a subject can earn in the RF stage is 6 Euro (if she spends no time waiting at traffic lights), and the most she can earn if she waits is 4 Euro (if she waits exactly 5 s at each light). In the instructions for the RF stage (see Appendix G) subjects are told: "*The rule is to wait at each stop light until it turns green*".[7] No other information, apart from the payment scheme and a general description of the walking procedure, is provided in the instructions.[8]

As noted by KV, the rule following task instructs subjects to follow a familiar rule at some cost to themselves. Obedience to this rule is "irrational" in the sense that with no monitoring or penalties, there is no cost to breaking the rule. In our experiment the typical justification for obeying traffic law is irrelevant because there are no other drivers or pedestrians to protect or be protected from and no police to impose fines – this is similar to a situation in which people wait at stoplights in the middle of the night, despite the absence of other pedestrians or drivers. In such risk-free settings, risk preferences cannot account for the decision to follow the rule, or, since individuals face a tradeoff between a higher payoff now and a lower payoff later, can standard models of discounting. Similarly, since subjects' RF decisions only affect their own payoffs, social preference models do not predict rule-following. Why then are individuals frequently willing to incur costs in service of such rules? We follow Kimbrough and Vostroknutov (2013) who argue that the decision to follow a costly rule (by waiting at the lights) reveals information about an individual's type: those who wait longer are more sensitive to social norms, and hence are hypothesized to better sustain CPRs. One related conjecture is that rule-following reveals an experimenter demand effect, but in fact, any such intrinsic concern for the norms of the laboratory setting – including respect for the demands of the experimenter – is very close to what we aim to measure. We use waiting times measured in the RF task to sort participants into groups in two treatments.

[7] KV report an additional "NoRule" treatment in which the phrase "the rule is …" is excluded from the instructions. The explicit statement of the rule substantially increases the rate of full compliance (from 12.5% to 62.5%) suggesting that the evoked context alone is not sufficient to induce much waiting.

[8] If a subject asked what would happen if he/she passed through the red light, an experimenter explained that all information relevant to the experiment is presented in the instructions.

CPR task

Before making decisions in the RF stage, subjects only receive instructions for that stage. In particular, they are aware that the experiment will consist of several stages, but they know neither what they will do in the next stage(s) nor the connection between the RF stage and consecutive stages.[9]

Unknown to the subjects, their decisions in the RF stage determine their group membership in the CPR game.

We employ the same matching procedure in both assortative matching treatments. First, we randomly divide subjects into groups of 8. Second, within each group of 8, we rank subjects according to the total time they spent waiting at traffic lights – at least 25 s for those subjects who waited for green at all traffic lights and close to 0 s for those who did not wait at any traffic light. Then, in each group of 8, we separate the top 4 subjects (rule-followers) and the bottom 4 subjects (Rule-Breakers) into two groups for stage 2. After we match subjects, there is no interaction between any groups of 4. Subjects are not informed about the matching procedure, and they are told only that they will now interact with a fixed group of three other participants (see Appendix H).

In all treatments the CPR game is played in each group of 4 subjects for 10 periods. However, subjects are not informed how many periods of the CPR task they will perform. The instructions in Appendix H specify that the game will be played for *several* periods. An indefinite ending point should provide a best-case scenario for cooperation, regardless of treatment.

Subjects are told that in each period they will collect 60 tokens from a group account and a private account. Their decision is how many of these 60 tokens to take from each account. Each token taken from the private account yields a return of 1 Euro cent per token. Whereas, each token taken from the group account generates a return of 2 Euro cents. Token supply in the private account is unlimited, which means that each subject can take as many tokens as she wishes from the private account in each period (subject to the 60 token limit). However, the group account, from which all four subjects can take tokens, has a limited capacity and initially contains a total of 360 tokens. Whenever subjects take tokens from the group account, its size diminishes by the sum of tokens taken. Before the next period, the group account replenishes: if there are X tokens remaining, then next period the group account will contain $X+\beta(360-X)$ tokens (here β is the treatment-dependent growth rate). However, if the number of tokens remaining falls below 30, then the group account would not replenish. Finally, if subjects choose to take more tokens than there are in the group account, tokens are divided among subjects who have chosen non-zero effort according to the simultaneous eating algorithm. Thus, in CPRH treatment the parameters are as follows: $\overline{w}=360, \overline{e}=60 n=4; \beta=0.5, \tau=30, \alpha=2, L=10, M=2$ (M is calculated from other parameters, see Lemma 1). Notice that with these parameters we have

$$\beta > \frac{\tau(n-1)}{\overline{w}-\tau}$$

which means that the SPNE (without norms) is to preserve the resource indefinitely (see Proposition 2).

The CPRL treatment is the same as CPRH except for one change. Here $\beta=0.25$ and thus is lower than in the CPRH treatment. This switches the sign of the inequality above so that the SPNE (without norms) is as depicted in Proposition 3 and the resource will be rapidly depleted in equilibrium. To isolate the impact of varying β in the absence of sorting we ran two additional treatments where the order of the tasks was reversed and subjects were placed into groups at random (revCPRL and revCPRH). In Appendix F we also report an exponential growth treatment, where a different resource regeneration function was used (CPREXP). Finally, at the end of the experiment, subjects filled out the Moral Foundations Questionnaire (Haidt, 2007), which provides estimates of subjects concerns for 5 fundamental moral issues.

Overall, 88 subjects participated in the CPRH treatment; 96 subjects in the CPRL treatment; 24 subjects in revCPRH; 32 subjects in revCPRL; and 56 in CPREXP (reported in Appendix F). No pilots or other treatments were run. All experiments were conducted at the Behavioral and Experimental Economics Laboratory (BEELab) at Maastricht University in October–November 2011. Experiments were programmed in *z*-Tree (Fischbacher, 2007). The subject pool consisted of the undergraduate students at Maastricht University. The recruiting was done through the Online Recruitment System for Economic Experiments (ORSEE). The participants earned an average of 12 Euro. We substituted earnings from the RF task for the show up fee. Experimental instructions (see Appendices G and H) describe the tasks in terms of “tokens” that could yield 1 or 2 Euro cents depending on the choices of the participants. A typical session lasted 45 min with 15 min for instructions. No deception was used throughout the experiment.

[9] Specifically, subjects' rule-following task instructions read “Part I” at the top of the page (see Appendix G). Some might be concerned that the foreknowledge of a second task will influence behavior in the first task. However, as noted in a previous implementation of a similar experimental design in Kimbrough and Vostroknutov (2013):

> In dictator game experiments, knowledge of the existence of an unspecified second-stage has been shown to alter subjects' behavior by making them more cooperative in expectation that their first-stage behavior may influence their second-stage reputation (Smith, 2008). If subjects are concerned for their reputation and thus wait longer than they might in a treatment without an implicit “shadow of the future” (or, similarly, with a double-blind protocol), this would dilute the information content of the rule-following task, thereby strengthening our results.

Related experiments

The pioneering CPR experiments are Gardner et al. (1990), Walker et al. (1990), and Walker and Gardner (1992) and here (1) the stage game has a NE which is close to the social optimum and in which the CPR is not depleted, and (2) there is no path-dependence of resource stocks on past choices. The main finding is excess depletion of the resource; when "individuals do not know one another cannot communicate effectively, and thus cannot develop agreements, norms, and sanctions," groups are prone to the "tragedy of the commons" (Ostrom et al., 1994a). In our experiment the stage game has a NE outcome in which the resource is totally depleted; thus resource stocks may be very difficult to sustain. More recent experiments with CPR games follow four main paths: (1) asymmetric CPR games which mimic specific problems found in the field (Cárdenas et al., 2011; Janssen et al., 2011); (2) studies that investigate how different institutional arrangements influence CPR extraction (Cárdenas and Ostrom, 2004; Cárdenas et al., 2011; Rodriguez-Sickert et al., 2008); (3) studies that compare behavior to models of various preference structures (Velez et al., 2009; Fehr and Leibbrandt, 2011); (4) models of CPR with sanctions (Cárdenas, 2011). All these studies use the classical CPR game as introduced by Walker and Gardner (1992), which by the static nature of the game does not allow them to answer questions related to resource regrowth. Neither does any of them employ assortative matching.

Fehr and Leibbrandt (2011) study the connection between impatience and cooperation in the classic CPR game. In a field/experimental study they find that impatient shrimpers tend to use nets with smaller holes and overharvest shrimp. Even though this finding is intriguing, our RF task cannot correlate with impatience measures since in the RF task, subjects face a tradeoff between more money now or less money later. Rule-followers choose to lose money for some intrinsic reasons which are not connected to any possible rewards in the future. It is an interesting, but separate, question whether measures of time preference correlate with our RF task, but there is no obvious theoretical connection.

The experiment most similar to ours is the Forestry Game reported in Cárdenas et al. (2011). Analogously to our experiment the resource grows after each period. The growth is very slow and the resource is quickly depleted in all groups. This is in line with our results: participants cannot sustain the resource with low growth rates. Another experiment with resource regrowth is conducted by Bru et al. (2003). Their game is rather different from ours (players move sequentially), but the authors also find overharvesting. A somewhat different setup is used in Janssen et al. (2010) and Janssen (2013), where participants control virtual avatars as they travel around an on-screen matrix and collect tokens, which regrow with time. Overharvesting is immanent, however it is mitigated by communication and punishment. Janssen (2010) reports additional experiments using the same experimental environment and exploring the effects of communication and punishment on the endogenous creation of informal CPR management institutions under different resource growth rates, and he reports that groups tend to preserve the resource successfully whether growth is high or low, in line with previous experiments on the effects of communication and punishment on CPR management.

Several studies consider theoretical models of dynamic CPR games with some dependency between periods. Fischer et al. (2004) consider an intergenerational CPR game in which each subsequent generation inherits the resources left by the previous generation. From a game theoretic perspective, this model has no strategic component since the players in each period are different. In our model players are fixed throughout the game, thus creating behavior which is forward-looking and strategic. Botelho et al. (2014) analyze a dynamic CPR game with uncertainty. In their model players face a CPR game with a stochastic resource stock in each period. It should be noted that this game is the same each period, and there is no dependency between periods. Our model does not introduce resource stock uncertainty, but has between period dependency. It is hard to compare the two approaches as the questions asked in our paper and Botelho et al. (2014) are rather different. Muller and Whillans (2008) look at a continuous dynamic system in which agents extract resources in each period and the stock regrows afterwards. They model it as a system of differential equations which describe growth and extraction in time. However, the authors do not consider maximization behavior of the agents and instead compare the experimental data with the steady state. This makes this model very different from ours since we examine individual utility maximization in a strategic environment. Cárdenas (2013) aims to justify cooperation in repeated CPR game by means of reinforcement-learning process in which all extraction choices can be made with non-zero probabilities which evolve over time. We think that learning in CPR systems is likely quite important, however, we focus on social norms in our approach.

Finally, it is worth mentioning an experiment by Schill et al. (2015). The authors focus on communication among players who try to sustain dynamic CPR, which regrows between periods. Two similarities to our experiment are the existence of a threshold, below which the growth is very slow (in our case – zero) and varying growth rate that depends on the amount of the resource.

Experimental findings

Ecological variables

First we report tests of the basic model without norms Propositions 2 and 3. Fig. 3 displays average resource dynamics across all treatments. In the SPNE of the dynamic game with CPRH parameters ($\beta = 0.5$), all groups should sustain the resource for the full 10 periods, and with CPRL parameters ($\beta = 0.25$), SPNE play exhausts the resource in period 2. While behavior is not strictly consistent with the SPNE, it is clear that the growth rate (β) substantially impacts the path of the resource over time.[10] In the CPRH treatment, only rule-breaking groups deplete the resource below τ on average, and only in

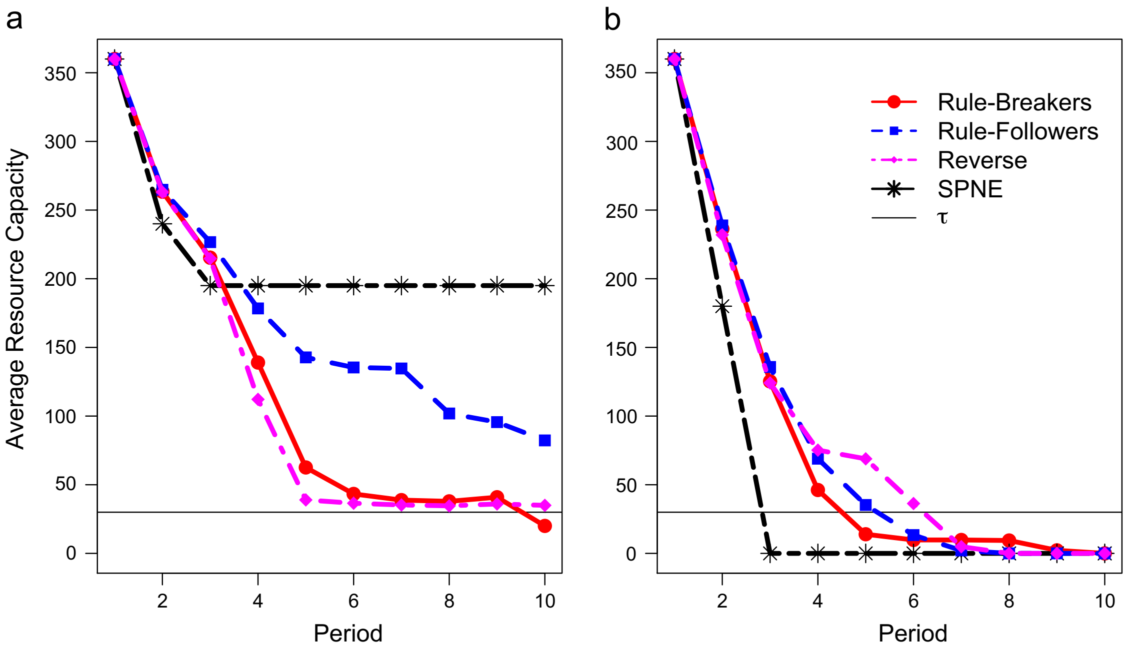

Fig. 3. Time series of resource stocks by treatment.

the final period. In the CPRL treatment, though, all group types deplete the resource below τ by the 7th period, and the resource is completely depleted by the 10th period.

For statistical support, we compute a variable called exhaustion for each group in each treatment; exhaustion measures the period in which the resource was first depleted (i.e. $t|w_t<\tau$). If the group never exhausts the resource, exhaustion $=11$. Permutation tests demonstrate that the mean period of exhaustion is later in the CPRH treatment (means are 6.6 and 4.7 in the CPRH and CPRL treatments, respectively; $p-\text{value}=0.001$, one-sided test).[11] Thus, our evidence is at least qualitatively consistent with the comparative static predictions of the model. We summarize our first finding.

Finding 1. As predicted by the model Propositions 2 and 3. differences in the resource regeneration rate, β, lead to significant differences between the CPRL and CPRH treatments. Comparing all groups in each treatment, the resource is exhausted later in the CPRH treatment. However, consistent with Ostrom et al. (1992), we observe over-harvesting relative to the Nash equilibrium when the resource should be preserved in equilibrium.

Social variables

Given that the data are inconsistent with the SPNE without norms as in Propositions 2 and 3, we consider the impact of assortative matching on RF task behavior. This allows us to compare our data to the model with norms developed in Model with norms section.

RF task

Subject behavior in the RF task is used to assign individuals to groups of rule-followers and rule-breakers. Figure F1 in Appendix F.1 displays histograms of total waiting time by group type in the CPRL and CPRH treatments, and Figure F2 displays the same information for the reverse and CPREXP treatments. Average waiting times in CPRH rule-breaking and rule-following groups are 14.8 and 27.8 s respectively. Similarly, average waiting times in CPRL rule-breaking and rule-following groups are 15.2 and 30.4 s. Due to our sorting mechanism sometimes individuals who broke the rule (i.e. waited less than 25 s) were placed in rule-following groups and vice versa. On average, in the CPRL and CPRH treatments, assortatively matched "rule-following groups" contained 0.5 rule-breakers and assortatively matched "rule-breaking groups" contained 3.3 rule-breakers.

[10] This is consistent with recent evidence suggesting that levels of cooperation across groups within the same society are sensitive to ecological variables (Lamba and Mace, 2011).

[11] Further evidence that low growth rates impede sustainability of the resource is provided by our CPREXP treatment in which growth rate was exponential (reported in Appendix F.4). An exponential regrowth function implies that growth is low for low resource stocks and high for high stocks, which is opposite to the CPRL and CPRH treatments. Subjects in the CPREXP treatment (both rule-breaking and rule-following groups) tend to exhaust the resource rather quickly.

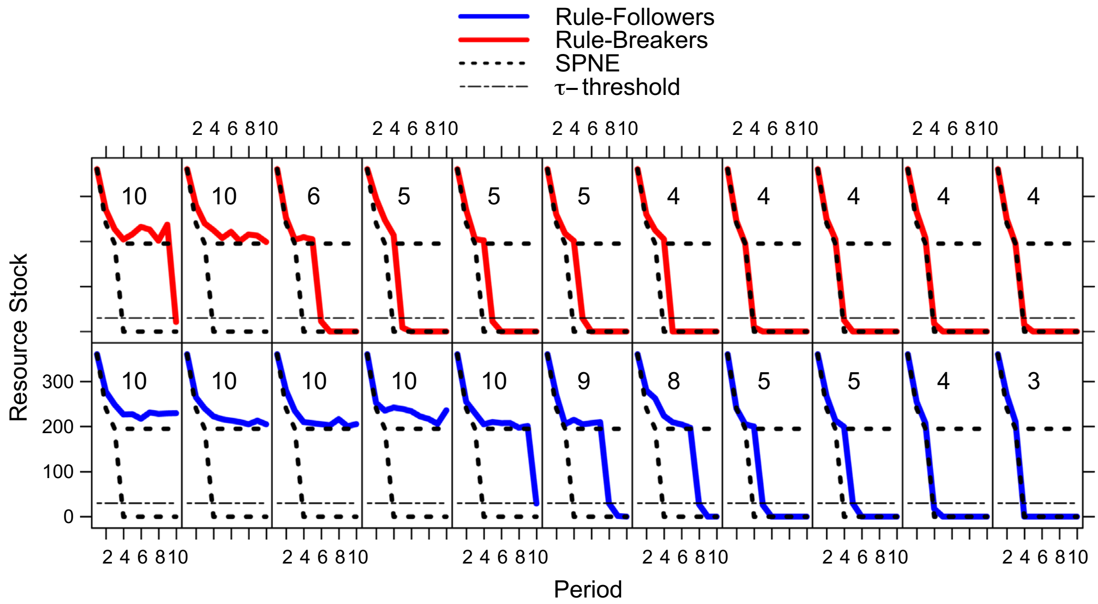

Fig. 4. Time series of resource stocks for individual groups in CPRH treatment. The top row shows rule-breaking groups, and the bottom row shows rule-following groups. The numbers in the middle of each panel indicate the period in which the group exhausted the resource (exhaustion). We plot the SPNE in which the resource is sustained as well as the SPNE with norms in which groups composed of 4 rule-breakers deplete the resource.

Linear regression analysis of total waiting time regressed on individual characteristics collected in our post-experiment questionnaire replicates the finding in KV that women wait longer on average than men and suggests that Law students spend less time waiting than others – here our baseline is international business majors (see Table F in Appendix F.5). We observe no differences across individuals of different nationalities, but we draw our subjects from a relatively homogeneous pool, mostly composed of western European individuals. We also find no evidence that subjects' moral foundations scores are correlated with rule-following proclivity.

CPRH treatment

While ecological variables play an important role in CPR maintenance, it is clear from Fig. 3 that there are also substantial differences between rule-breaking and rule-following groups. In particular, rule-following groups are substantially more successful at maintaining the resource than rule-breaking groups. Among rule-followers, 4 out of 11 groups (36%) sustain the resource at or above the equilibrium level for all 10 periods, while among rule-breakers there is only 1 such group (9%). More generally, 45% of rule-following groups sustained some amount of the resource for all 10 periods while only 18% of rule-breaking groups did so (see Fig. 4 for a time series for each group). The rest of the groups deviate from the SPNE (Proposition 2) and harvest the resource to depletion. A permutation test indicates that there is a significant difference in the mean period of exhaustion between rule-followers and rule-breakers in the CPRH treatment (means are 8 and 5.7, respectively; p-value $=0.039$, one-sided test).

What drives the differences in behavior between rule-following and rule-breaking groups shown in Fig. 4? In Model with norms section we outlined a simple modification of the game which includes two types of players: rule-followers, who receive additional utility from following the Social Planner's solution, and rule-breakers, who are purely selfish and choose maximal effort whenever they expect the resource to be depleted. We show that groups with many rule-breakers will exhaust the resource in one SPNE, while groups with few rule-breakers will sustain it. Fig. 4 shows the alternative equilibrium path for groups consisting of four rule-breakers in which the resource is rapidly depleted, and we observe that 4 rule-breaking and 2 rule-following groups follow this path exactly. Moreover, the model makes subtle predictions about differences in the distribution of efforts across rule-followers and rule-breakers in the period in which the resource is exhausted. In particular, rule-breakers should be more likely to exert full effort, and regression analysis reported in Appendix F.2 confirms these predictions. More generally, the model with norms implies a negative correlation between the period of exhaustion and the number of rule-breakers (i.e. individuals who waited less than 25 s in the RF task) in a group, and indeed this is what we observe (Spearman's $\rho=-0.46, p-\text{value}=0.016$, one-sided test).

The explanation above cannot account for all the group dynamics observed in Fig. 4. For example, some rule-following groups maintain the resource for 5–9 periods before suddenly exhausting it. This is driven by coordination failure, as the equilibrium is sensitive to trembles. To sustain the resource beyond period 2, 4 individuals must each expend effort less then or equal to $\frac{w_t-\tau}{4}$. Even if all four players seek to sustain the resource, they at the same time try to extract as much of it as possible. Thus, the resource stock may fall below τ if even *one* subject harvests more than $\frac{w_t-\tau}{4}$. Moreover, given that subjects' effort choices were integer constrained, when $(\frac{w_t-\tau}{4}\text{mod}4)\neq 0$, the coordination problem is even more complicated in practice than in theory. From Fig. 4 it is clear that at least some groups failed to solve this coordination problem. Specifically, note the number of cases in which the resource stock falls from around the equilibrium level at time $t>2$ into the interval $(0,\tau)$ at time $t+1$. In all such cases, $w_t > \sum_{i \in I} e_i > w_t - \tau$, which indicates that at least some subjects chose their effort levels with the τ threshold in mind.

Finding 2. In the CPRH treatment half of rule-following groups sustain the resource as the SPNE (without norms) predicts. However, contrary to this prediction, the remaining rule-following groups and almost all rule-breaking groups deplete the resource. The ability to sustain the resource depends critically on the presence of rule-followers, who receive additional utility from sustaining it. The presence of too many rule rule-breakers leads to the resource being exhausted. Finally, the coordination problem embedded in the SPNE can account for intermediate cases in which the resource is sustained for a few periods and then is suddenly depleted.

CPRL treatment

Now we compare the behavior of rule-following and rule-breaking groups in the CPRL treatment. In the CPRL treatment, *all* groups eventually exhaust the resource, which is qualitatively consistent with the SPNE (without norms) of the dynamic game with CPRL parameters. Strictly speaking, only 3 groups follow this equilibrium exactly and exhaust the resource in 2 periods (see Figure F4 in Appendix F). Instead, the majority of groups manage to sustain resource stocks at positive levels for 3 or more periods. A permutation test indicates that there is no significant difference in the mean period of exhaustion between rule-followers and rule-breakers in the CPRL treatment (means are 4.7 and 4.4, respectively; $p-\text{value}=0.40$, one-sided test). Here, given the slow rate of resource regeneration ($\beta=0.25$), subjects are unable to permanently sustain the resource above the τ threshold, regardless of their type.

To gain more insight into how subjects manage to sustain the resource for longer than two periods, we return to the model with norms developed in Model with norms section. As before, we assume there exists a prescriptive norm of following the Social Planner's solution to the CPR problem and that rule-followers gain additional utility for adhering to this norm. For the low growth rate, the model predicts that with few enough rule-breakers and strong enough desire to follow the norm among rule-followers, it is possible in equilibrium to sustain the resource. However, as compared to the CPRH case, rule-followers' utility for adhering to the norm must be much higher in CPRL (see Table 1). In our RF task rule-followers were willing to lose 2 Euro or more adhering to the rule for a mere 25 s. Thus, it is not inconceivable that if there are many strong rule-followers in a group, the resource can be sustained for some time, and we see evidence for this in Figure F4. Moreover, we see a significant negative correlation between the number of rule-breakers in a group and the period of exhaustion (Spearman's $\rho=-0.43, p-\text{value}=0.018$, one-sided test). Thus, group type composition can partly explain observed heterogeneous resource dynamics.

Nevertheless, the resource is eventually exhausted in all groups. This might also result from coordination failure, as described in the previous section, which is much more severe when the growth rate is low. This is simply because with the low growth rate the resource ends up in the “danger zone” from which the resource can be exhausted much more often than in the environment with high growth.

Finding 3. In the CPRL treatment all groups eventually exhaust the resource, though it takes them longer than 2 periods, and thus behavior deviates from the SPNE. The groups can sustain the resource for some time if there are many strong rule-followers. However, the resource is eventually exhausted because subjects face a coordination problem in each period before the resource is gone.

To summarize, we see that the dynamics of the resource in the CPR game depends on both ecological and social factors as well as strategic concerns (coordination problems). In order to achieve sustainability either ecological or social factors should be favorable enough. When the growth rate is high the resource can be sustained with relatively mild demands on rule-followers. When the growth rate is low the resource can be sustained only if there is sufficiently strong propensity among players to maintain it.

The role of assortative matching

In order to highlight the impact of assortative matching on outcomes, we examine resource dynamics in mixed-type groups composed of both rule-breakers and rule-followers. Here, subjects first play the CPR game in randomly matched groups of 4, and then they participate in the RF task. We call these reverse treatments, revCPRH and revCPRL. These treatments further allow us to distinguish the effects of our sorting mechanism based on the rule-following task.

Returning to Fig. 3 note that the dynamics in the revCPRH treatment are qualitatively similar to those observed in rule-breaking groups in the sorted CPRH treatment. Most groups do not immediately deplete the resource, but only one group sustains it for the full 10 periods (see Figure F5 in Appendix F). We can weakly reject the hypothesis of equal mean periods of exhaustion between rule-following groups in the CPRH treatment and the revCPRH treatment (means are 8 and 5.5, respectively, one-sided permutation test, p-value$=0.073$). A permutation test fails to reject the null if we compare rule-breaking groups in the CPRH treatment (mean 5.7) with revCPRH (p-value$=0.86$, two-sided test).

With a low growth rate, permutation tests cannot reject the null hypothesis of equal mean exhaustion when comparing revCPRL (mean $=5.1$) to either rule-followers or rule-breakers in the CPRL treatment (p-values$=0.51$ and 0.41, respectively, two-sided tests). Nevertheless, all but one group sustains the resource longer than predicted in the SPNE without norms, which suggests that rule-followers still try to preserve the resource, with varying degrees of success. Pooling the reverse treatments with their respective assortative matching treatments, we still find evidence of a significant negative relationship between the number of rule-breakers in a group and the period of resource exhaustion (Spearman's $\rho = -0.48$ and -0.29, p-values $= 0.005$ and 0.054, respectively for CPRH and CPRL, one-sided tests).

Finding 4. In the reverse treatments group dynamics are statistically indistinguishable from the dynamics of rule-breaking groups in the corresponding main treatments. Overall, these results are consistent with the intuition behind the model in Model with norms section; assortative matching of rule-followers is essential for sustaining the resource.

Conclusion

We report theory and experiment designed to disentangle the social and ecological determinants of common pool resource sustainability. In a novel dynamic model of a CPR system, we first show that under standard assumptions on agents' preferences, the ability to sustain the resource depends on ecological factors – in particular on the regrowth rate of the resource. Then, building on the framework developed in Kimbrough and Vostroknutov (2013), we introduce heterogeneous player types that vary in their intrinsic concern for following rules and social norms (we call them rule-followers and rule-breakers). Under the assumption that there exists a norm of preserving the resource – in line with the Social Planner's solution – we show that the presence of these types introduces new equilibria in which (1) resources that would have been depleted in the original SPNE can be preserved by groups of rule-followers and (2) resources that would have been preserved in the original SPNE may be depleted by groups of rule-breakers.

Data from laboratory experiments supports the comparative statics predictions of the baseline model when we compare behavior under two parameter configurations, one in which the resource is sustained in equilibrium and one in which it is exhausted. Nevertheless, individuals destroy the resource more frequently than predicted in the former case and maintain it for longer than predicted in the latter. We show that this behavior also varies with the behavioral-type composition of the group. Specifically, groups composed of rule-breakers are more likely to exhaust the resource than groups of rule-followers, consistent with our model in which rule-followers and rule-breakers care heterogeneously about adhering to the Social Planner's solution.

While our model helps to account for the diversity of outcomes in common pool resource management around the world, our experimental results show that subtle differences in group composition can also have large impacts. Successful resolution of social dilemmas can be facilitated by screening out non-cooperative types, and we show that one way of identifying those types is to observe their willingness to follow costly rules. Indeed, this is consistent with Ostrom's (2009) notion of “boundary rules”. This finding highlights the crucial role of screening, exclusion and assortative matching in the preservation of CPRs, and it reiterates the point that ecological factors are merely permissive and not prescriptive of any observed form of social organization (Algaze, 2005), thereby providing additional support for the social-ecological systems view of CPRs.

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Appendix A. Supplementary data

Supplementary data associated with this paper can be found in the online version at http://dx.doi.org/10.1016/j.jeem.2015.04.004.

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The Social and Ecological Determinants of Common Pool Resource Sustainability

Online Appendix

A Simultaneous Eating Algorithm

In this section we formally describe the function $p_i(e_i, e_{-i})$ that determines the amount of resource that is received by player i in case the sum of efforts exceeds the available resource. Throughout this section the notation of Section 2.1 is maintained.

To begin consider a structure $\langle T, S, f : S \to \mathbb{R}_+ \rangle$. Here $T > 0$ is the amount of available resource, S is a non-empty subset of players and $f(s)$ represents the effort chosen by player $s \in S$. It is assumed that $\sum_{s \in S} f(s) > T$, i.e. that the sum of efforts of players in S exceeds the available resource T (otherwise the algorithm does not apply). Let ε denote the smallest effort level chosen by players in S and $n_S = |S|$ be the cardinality of S. If $\varepsilon n_S < T$ set $p_i(e_i, e_{-i}) = e_i$ for all i with $f(i) = \varepsilon$. If $\varepsilon n_S \geq T$ set $p_i(e_i, e_{-i}) = T/n_S$ for all $i \in S$. By means of this construction we define the function $p_i(e_i, e_{-i})$ for some players in a subset S of all players.

Now, to define $p_i(e_i, e_{-i})$ for all players we will use the above construction recursively. Start from the effort levels $e_1, ..., e_n$ and some available resource E (in notation of Section 2.1) and consider a structure $\langle E, \{1, .., n\}, (e_i)_{i \in \{1,..,n\}} \rangle$. This structure sets the values of $p_i(e_i, e_{-i})$ for some players in a subset $G \subseteq \{1, .., n\}$. If $G = \{1, .., n\}$ stop the algorithm, as in this case $p_i(e_i, e_{-i})$ is set for each player i. If $G \subsetneq \{1, .., n\}$ then $p_i(e_i, e_{-i})$ is set only for players $i \in G$ who exerted the smallest effort ε. Now let $n_G = |G|$ be the cardinality of G and consider a structure $\langle E - \varepsilon n_G, \{1, .., n\} \backslash G, (e_i)_{i \in \{1,..,n\} \backslash G} \rangle$. Set $p_i(e_i, e_{-i})$ for a subset of $\{1, .., n\} \backslash G$ as described above. Continue the procedure until $p_i(e_i, e_{-i})$ is defined for all players.

B Proofs

Proposition 1. *If $w > n\bar{e}$ then the unique pure strategy Nash Equilibrium of the w-game is $e_i = \bar{e}$ for all $i = 1..n$. If $w \leq n\bar{e}$ then any vector $(e_i)_{i=1..n}$ with $e_i \geq \frac{w}{n}$ for all i is a pure Nash Equilibrium of w-game.*

Proof of Proposition 1. If $w > n\bar{e}$ it is obvious that only the first case in the definition of π_i can occur, or $\pi_i(e_i, e_{-i}) = \bar{e} + (\alpha - 1)e_i$. Therefore, since $\alpha > 1$, the only strictly undominated action is $e_i = \bar{e}$ for all i which results in the proposed NE. ▲

If $w \leq n\bar{e}$ then the following cases are possible. First, suppose that $E < w$, then for each player i it is true that $\pi_i(e_i, e_{-i}) = \bar{e} + (\alpha - 1)e_i$. Moreover, it cannot be true that all players exert effort $\bar{e}$. Thus, there exists player j who can profitably deviate by increasing her effort a little bit so that the sum of efforts is still less than w. Therefore, $E < w$ cannot happen in equilibrium.

Second, suppose that $E \geq w$, then there are potentially two types of players: 1) those who have $p(e_i, e_{-i}) = e_i$ (they have exerted chosen effort before the resource was exhausted) and 2) the rest who exerted too much effort and thus shared the remains of the resource equally. Any player of the first type can increase her effort by a small amount and still stay in the category of players who have exerted their efforts before the exhaustion. Therefore, in equilibrium players of the first type cannot exist. This leaves only the case when *all* players are of the second type. Namely, all players choose efforts high enough so that no player exerts chosen effort before the resource is exhausted. This necessarily implies that $e_i \geq \frac{w}{n}$ for all i. Any combination of efforts with this property is NE since increasing effort does not change the payoff and decreasing effort weakly decreases it. ■

* * *

Proposition 2. *If $\beta \geq \frac{\tau(n-1)}{\overline{w}-\tau}$ and $\tau \leq \bar{e}$ then the following strategy used by all players constitutes a SPNE. In periods $t = 1..L$ choose $e_{it} = \bar{e}$ if the resource before period t is $w_t \geq n\bar{e} + \tau$. In period $t = 1..L-1$ choose $e_{it} = \frac{w_t - \tau}{n}$ if $w_t \in [\tau, n\bar{e} + \tau)$ and $e_{it} = \frac{w_t}{n}$ if $w_t < \tau$. Choose $e_{iL} = \min\{\bar{e}, \frac{w_L}{n}\}$ if $w_L < n\bar{e} + \tau$.*

Proof of Proposition 2.[1] The proof consists of several cases. However let us make some observations beforehand. First, suppose that the amount of resource before some period is $w > n\bar{e} + \tau$. Then, even if all players choose maximal effort $\bar{e}$, the available amount of the resource at the beginning of the next period will be higher or equal to that in the current period as long as $w - n\bar{e} + \beta(\overline{w} - (w - n\bar{e})) = (1-\beta)(w - n\bar{e}) + \beta\overline{w} \geq w$. This can be rearranged to $w \leq \overline{w} - \frac{1-\beta}{\beta} n\bar{e}$. This means that for any values of the resource less than the right hand side even if all players choose maximal efforts the next period resource will be higher or equal to the original one. Notice that RHS can be negative (if β or $\overline{w}$ is low). This means that for some combinations of parameters, the above statement will never hold. Second, for values $w > \overline{w} - \frac{1-\beta}{\beta} n\bar{e}$ if all players exert maximum effort, then the amount of the resource before next period will drop. However, if

$$\overline{w} - \frac{1-\beta}{\beta} n\bar{e} \geq n\bar{e} + \tau \tag{7}$$

then even if w is above the threshold $\overline{w} - \frac{1-\beta}{\beta} n\bar{e}$, all players can exert full effort $\bar{e}$ and still have access to a resource level greater than $n\bar{e} + \tau$ next period. To see this rearrange inequality (7) to get

$$\tau + \beta(\overline{w} - \tau) \geq n\bar{e} + \tau. \tag{8}$$

The LHS of this inequality is the amount of resource available following periods in which the resource was harvested so that the remaining quantity was τ, the minimum level at which the resource will regrow. This inequality says that even if the resource level reaches τ, regrowth will

[1]In the proof we will slightly abuse notation. Remember that utility in each period of the dynamic game is defined in equation (1). Since in almost all cases in the proof we will only use the first part of the utility which is $\pi_i(e_i, \cdot) = \bar{e} + (\alpha - 1)e_i$, we will drop $\bar{e}$ and $\alpha - 1$ and think of utility as just being $\pi_i(e_i, \cdot) = e_i$. This does not change any results.

ensure that enough of the resource is available in the following period for all players to exert the maximum effort, $\bar{e}$.

Case 1.1: $\boldsymbol{\overline{w} - \frac{1-\beta}{\beta} n\bar{e} \geq n\bar{e} + \tau}$ **and** $\boldsymbol{w_1 \geq n\bar{e} + \tau}$**.**
As was described above, if before period 1 $w_1 \geq n\bar{e} + \tau$ then players can exert maximal efforts *after all histories* in all periods until the end of the game. Moreover, inequality (8) guarantees that after no history will the amount of resource available be below $n\bar{e} + \tau$. The strategy proposed in this Proposition has all players choosing $\bar{e}$ after each history. This is a SPNE since choosing $\bar{e}$ gives all players the maximum attainable payoff in each period.

Case 1.2: $\boldsymbol{\overline{w} - \frac{1-\beta}{\beta} n\bar{e} \geq n\bar{e} + \tau}$ **and** $\boldsymbol{w_1 \in [\tau, n\bar{e} + \tau)}$**.**
If $w_1 \in [\tau, n\bar{e} + \tau)$ then in period 1 players choose $e_{i1} = \frac{w_1 - \tau}{n}$ and then choose $\bar{e}$ in all consecutive periods. According to the "one-stage-deviation principle" we should only check for deviations in period 1 (again because in all other periods players have maximal payoffs). In period 1 player i can increase that period's payoff by choosing effort $e_{i1} = \frac{w_1 - \tau}{n} + \varepsilon$, where $0 < \varepsilon < \tau$.[2] After this (and assuming all other players stick to the original strategy) the resource will drop to level $\tau - \varepsilon$, thus creating no growth afterwards. Therefore, following the strategy in all consecutive periods i will get $\frac{w_1 - \tau}{n} + \varepsilon + \frac{\tau - \varepsilon}{n}$. The last term here represents the payoff in second period. This deviation is not profitable as long as

$$\frac{w_1 - \tau}{n} + \varepsilon + \frac{\tau - \varepsilon}{n} \leq \frac{w_1 - \tau}{n} + (L-1)\bar{e}.$$

To check whether this holds for all deviations ε let us take a limit of the LHS to get the maximum possible deviation:

$$\lim_{\varepsilon \uparrow \tau} \frac{w_1 - \tau}{n} + \varepsilon + \frac{\tau - \varepsilon}{n} = \frac{w_1 - \tau}{n} + \tau \leq \frac{w_1 - \tau}{n} + (L-1)\bar{e}.$$

This holds whenever $\tau \leq (L-1)\bar{e}$ which is true by assumption of the Proposition. Therefore, the above strategy constitutes a SPNE.

Case 1.3: $\boldsymbol{\overline{w} - \frac{1-\beta}{\beta} n\bar{e} \geq n\bar{e} + \tau}$ **and** $\boldsymbol{w_1 < \tau}$**.**
Finally if $w_1 < \tau$ then no growth will happen in the game. In period 1 player i exerts effort $\frac{w_1}{n}$. By choosing more effort she will be worse off in period 1 and still get 0 in all consecutive periods. She can also deviate by choosing less effort: $\frac{w_1}{n} - \varepsilon$. However, in this case her payoff will be $\frac{w_1}{n} - \varepsilon + \frac{\varepsilon}{n}$. Where the last term corresponds to the payoff in period 2. It is clear that this deviation is not profitable. Profitable deviations in periods other than 1 are impossible because $w_2 = ... = w_L = 0$. Thus we have a SPNE. ▲

Next we analyze the case in which $\overline{w} - \frac{1-\beta}{\beta} n\bar{e} < n\bar{e} + \tau$. Notice that, analogously to inequality

[2] Notice that *decreasing* effort in period 1 cannot increase player i's payoff since she will still get maximal utility from putting effort $\bar{e}$ in all following periods.

(8), we have now $\tau + \beta(\overline{w} - \tau) < n\bar{e} + \tau$. This implies that if after some period the amount of resource is τ, then before next period the growth of the resource will be insufficient to allow all players to choose $\bar{e}$ without depleting the resource.

Case 2.1: $\overline{w} - \frac{1-\beta}{\beta} n\bar{e} < n\bar{e} + \tau$ and $w_1 \in [\tau, n\bar{e} + \tau)$.

Assume that $w_1 \in [\tau, n\bar{e} + \tau)$. Then, given the above observation, if players follow the strategy given in this Proposition they should choose effort $e_{it} = \frac{w_t - \tau}{n}$ in periods 1 through $L-1$ and $e_{iL} = \min\{\bar{e}, \frac{w_L}{n}\}$ in the last period. Let us check that there are no possible one period deviations from this strategy. On the proposed path player i gets payoff

$$\frac{w_1 - \tau}{n} + k\frac{(1-\beta)\tau + \beta\overline{w} - \tau}{n} + \min\left\{\bar{e}, \frac{(1-\beta)\tau + \beta\overline{w}}{n}\right\} \tag{9}$$

where $k = L - 2$.

Player i might deviate by exerting less effort: $\frac{w_1-\tau}{n} - \varepsilon$. In this case new payoff is

$$\frac{w_1 - \tau}{n} - \varepsilon + \frac{(1-\beta)(\tau+\varepsilon) + \beta\overline{w} - \tau}{n} + (k-1)\frac{(1-\beta)\tau + \beta\overline{w} - \tau}{n} + \min\left\{\bar{e}, \frac{(1-\beta)\tau + \beta\overline{w}}{n}\right\}.$$

This is a decreasing function of ε which equals to the on-the-path payoff if $\varepsilon = 0$.[3] Thus decreasing effort in period 1 is not profitable. This reasoning does not depend on number of periods k, therefore, the same logic can be applied to any period from 2 to $L-1$ to show that decreasing effort is not profitable. In period L all players play NE of the stage game therefore no deviations can occur there either.

Let us now check if player i could gain by increasing effort in period 1. Deviation gives the payoff $\frac{w_1-\tau}{n} + \varepsilon + \frac{\tau-\varepsilon}{n}$ which is an increasing function of ε. Therefore the best deviation is given by the limit of this expression when $\varepsilon \to \tau$ which is

$$\frac{w_1 - \tau}{n} + \tau.$$

In order for the deviation to be unprofitable this must be less then or equal to the on-the-path payoff in expression (9) for all values of k. Expression (9) increases in k, therefore the most constraining case is $k = 0$.

Deviation, thus, is unprofitable whenever (after rearranging given $k = 0$)

$$\tau \leq \frac{\beta\overline{w}}{\beta + n - 1} \qquad \text{and} \qquad \tau \leq \bar{e} \tag{10}$$

Both inequalities hold by the assumption of the Proposition.

Case 2.2: $\overline{w} - \frac{1-\beta}{\beta} n\bar{e} < n\bar{e} + \tau$ and $w_1 \geq n\bar{e} + \tau$ and small L.

[3] If ε is so big that before second period the resource is above $n\bar{e} - \tau$, then everyone will exert effort $\bar{e}$ which still makes this payoff function decreasing in ε.

Now let us assume that $w_1 \geq n\bar{e} + \tau$. It is clear that at least in period 1 all players can exert effort $\bar{e}$ and not deplete the resource below level τ. In general, by Lemma 1 with $W = n\bar{e} + \tau$ if all players exert effort $\bar{e}$ in all periods then there exists $M \in \mathbb{N}$ such that for all $k < M$, $w_k \geq n\bar{e} + \tau$, and for all $k \geq M$, $w_k < n\bar{e} + \tau$. Therefore, if $L < M$ then all players will receive the maximum payoff $\bar{e}$ in each period, which implies the absence of profitable deviations. Thus, if $L < M$ then in SPNE all players put in effort $\bar{e}$ in all periods.[4]

Case 2.3: $\overline{w} - \frac{1-\beta}{\beta} n\bar{e} < n\bar{e} + \tau$ and $w_1 \geq n\bar{e} + \tau$ and large L.
If, however, $L \geq M$ then there are periods at the end of the game in which the size of the resource falls below $n\bar{e} + \tau$ if all players exert effort $\bar{e}$ in periods before Mth. The strategy in this Proposition says that players should put in effort $\bar{e}$ in periods 1 through $M - 1$; put in effort $\frac{w_k - \tau}{n}$ in periods $k = M..L - 1$; and effort $\min\{\bar{e}, \frac{w_L}{n}\}$ in period L. By Case 2.1 above we know that no single period deviations are possible in periods M through L. Thus, it is only left to check single deviations in periods 1 to $M - 1$.

First, let us make an observation. By Lemma 1 we know that in periods 1 to M the size of the resource before period t is defined by $w_t = (1 - \beta) w_{t-1} + \beta c$, where $c = \overline{w} - \frac{1-\beta}{\beta} n\bar{e}$.[5] Suppose that in some period t the amount of the resource increases by some ε: $w'_t = w_t + \varepsilon$. Then in period $t + 1$ the changed amount of the resource will be $w'_{t+1} = (1 - \beta) w'_t + \beta c = w_{t+1} + (1 - \beta)\varepsilon$. Analogously, $w'_{t+k} = w_{t+k} + (1 - \beta)^k \varepsilon$. Therefore, an ε increase in the resource in period t increases the resource in period $t + k$ by $(1 - \beta)^k \varepsilon$ as long as all players exert effort $\bar{e}$ in the interim periods.

Now consider a small reduction in effort in period $M - 1$ by player i keeping the prescribed strategy of the rest of the players fixed. Remember, by construction, $w_{M-1} \geq n\bar{e} + \tau$ and $w_M < n\bar{e} + \tau$. Suppose player i decreases his effort in period $M - 1$ from $\bar{e}$ to $\bar{e} - \varepsilon$ with very small ε. This, as described in the previous paragraph, will lead to change in w_M: it will become $w_M + (1 - \beta)\varepsilon$. Now, as long as $w_M + (1 - \beta)\varepsilon \leq n\bar{e} + \tau$ the strategy prescribes all players to choose effort $\frac{w_M + (1-\beta)\varepsilon - \tau}{n}$. Since after this the resource level will fall to τ, the introduction of small ε will not have any effect on the payoffs in periods $M + 1$ onwards. Therefore, ε changes the overall payoff of player i by $-\varepsilon + \frac{(1-\beta)\varepsilon}{n} < 0$. So we might conclude that it is not worthwhile for player i to decrease her effort by the amount ε if $w_M + (1 - \beta)\varepsilon \leq n\bar{e} + \tau$.

However, this is not enough to conclude that no single deviation in period $M - 1$ is possible because a larger decrease in effort could also be profitable. For example, if player i chooses $\varepsilon > \varepsilon_1$ where ε_1 satisfies $w_M + (1 - \beta)\varepsilon_1 = n\bar{e} + \tau$. As $\varepsilon > \varepsilon_1$ we still have resource level $w_M + (1 - \beta)\varepsilon$ in period M. Now though $w_M + (1 - \beta)\varepsilon > n\bar{e} + \tau$, which means that player i in period M should choose $\bar{e}$ regardless of ε. This in its turn implies that now w_{M+1} will start changing to $w_{M+1} + (1 - \beta)^2 \varepsilon$. Overall change in payoff at ε_1 as was noticed above was $-\varepsilon_1 + \frac{(1-\beta)\varepsilon_1}{n} < 0$. As ε grows above ε_1 the payoff in period M stays fixed at $\bar{e}$, thus not influencing the difference in overall payoffs. However, the change in period $M + 1$ now takes effect and creates an overall change in

[4]See Lemma 1 for the exact formula for M in terms of the parameters of the model.

[5]If players stick to the strategy prescribed by this Proposition.

payoff for $\varepsilon > \varepsilon_1$ to be $-\varepsilon + \frac{(1-\beta)^2\varepsilon}{n} < 0$ as long as $\varepsilon < \varepsilon_2$ which satisfies $w_{M+1} + (1-\beta)\varepsilon_2 = n\bar{e} + \tau$. Thus a larger deviation resulting from choosing ε above ε_1 is even less profitable.

We can extend this argument and construct ε_3, ε_4, etc. tracking the change in overall payoff to see that the more ε increases the more negative the overall change in payoff becomes. Therefore we can conclude that decreasing effort in period $M-1$ for player i is not profitable.

Now suppose that player i *decreases* effort in period $M-2$ and it becomes $\bar{e} - \varepsilon$. As a result, the resource level in period $M-1$ will become $w_{M-1} + (1-\beta)\varepsilon$. But since in period $M-1$ player i already exerts effort $\bar{e}$, an increase in the resource level will have no effect on the payoff in period $M-1$. However, an ε change in $M-2$ will increase the resource size to $w_M + (1-\beta)^2\varepsilon$ in period M. Using the argument developed above, for $\varepsilon \leq \varepsilon_1'$ which satisfies $w_M + (1-\beta)^2\varepsilon_1' = n\bar{e} + \tau$, the overall change in payoff will be $-\varepsilon + \frac{(1-\beta)^2\varepsilon}{n} < 0$. For $\varepsilon > \varepsilon_1'$ the argument goes exactly as before and demonstrates that in period $M-2$ it is also not profitable to deviate from the prescribed strategy. Analogous arguments can be given for all periods $k = 1..M-3$.

We showed that there exists no single period deviation in any period by which player i can profitably deviate from the strategy given in the Proposition. Therefore we have a SPNE.

Case 2.4: $\overline{w} - \frac{1-\beta}{\beta}n\bar{e} < n\bar{e} + \tau$ and $w_1 < \tau$.
Same as Case 1.3. ■

* * *

Proposition 3. *If $\beta \leq \frac{\tau(n-1)}{\overline{w}-\tau}$, $n\tau < (n-1+\beta)\bar{e}$ and $\overline{w} \leq (n+(n-1)(1-\beta))\bar{e}$ then the following strategy used by all players constitutes a SPNE. In period $t = 1..L-1$ choose $e_{it} = \bar{e}$ if the resource before period t is $w_t \geq n\bar{e} + \tau$. In period $t = 1..L-1$ choose $e_{it} = \frac{w_t - \tau}{n}$ if $w_t \in (n\bar{e} + \tau - \frac{\beta(\overline{w}-\tau)}{n-1}, n\bar{e} + \tau)$. In period $t = 1..L-1$ choose $e_{it} = \min\{\bar{e}, \frac{w_t}{n}\}$ if $w_t \leq n\bar{e} + \tau - \frac{\beta(\overline{w}-\tau)}{n-1}$. Choose $e_{iL} = \min\{\bar{e}, \frac{w_L}{n}\}$ for all w_L.*

Proof of Proposition 3. Some observations first. Notice that the restrictions on τ in this Proposition imply

$$(1-\beta)\tau + \beta\overline{w} \;\leq\; n\tau \;<\; n\bar{e} \quad \text{and} \quad \frac{\beta(\overline{w}-\tau)}{n-1} \leq \tau. \tag{11}$$

Moreover, the following equivalence holds:

$$(1-\beta)\tau + \beta\overline{w} \;\leq\; n\bar{e} \quad \Longleftrightarrow \quad \overline{w} - \frac{1-\beta}{\beta}n\bar{e} \;\leq\; n\bar{e} - \frac{1-\beta}{\beta}\tau \;<\; n\bar{e}. \tag{12}$$

Case 1: $w_1 \in (0, n\tau)$.
Here no player can deviate in period 1 so that the resource reaches the level where it can grow next period. Exerting ε less effort in period 1 gives payoff $\frac{w_1}{n} - \varepsilon + \frac{\varepsilon}{n}$. This is decreasing in ε, thus no profitable deviation is possible.

Case 2: $w_1 \in [n\tau, n\bar{e})$.
Here $w_1 \geq n\tau$ which implies that one player can deviate from the strategy described in the Propo-

sition (choose $\frac{w_1}{n}$) so that resource is depleted to the level at least or above τ. On (proposed) equilibrium path payoff in this case is $\frac{w_1}{n}$ and the deviation payoff is $\frac{w_1}{n} - (\tau+\varepsilon) + \frac{(1-\beta)(\tau+\varepsilon)+\beta\overline{w}}{n}$. Here one player exerts effort $\frac{w_1}{n} - (\tau+\varepsilon)$ instead of prescribed $\frac{w_1}{n}$. It is clear that deviation payoff decreases in ε, thus the best deviation payoff is $\frac{w_1}{n} - \tau + \frac{(1-\beta)\tau+\beta\overline{w}}{n}$. Notice that due to (11) players can deplete the resource to zero in the second period after deviation, so no min operator on $\frac{(1-\beta)\tau+\beta\overline{w}}{n}$ is required. No deviation occurs if (after rearranging) $\tau \geq \frac{\beta\overline{w}}{\beta+n-1}$, exactly as assumed in the Proposition.

Case 3: $w_1 \in [n\bar{e}, n\bar{e}+\tau-\frac{\beta(\overline{w}-\tau)}{n-1}]$.
In this case according to the Proposition all players should exert effort $\bar{e}$, which will exhaust the resource below τ. Thus on the equilibrium path each player gets

$$\bar{e} + \frac{w_1 - n\bar{e}}{n}.$$

If one player decides to decrease her effort by a small $\varepsilon > 0$, then she will get $\bar{e} - \varepsilon + \frac{w_1+\varepsilon-n\bar{e}}{n}$, which decreases in ε. Thus, small deviations are not profitable. A player might also decrease her effort by a higher amount, so that the resource after efforts becomes $\tau+\varepsilon$ and as a result grows before the next period. In this case the payoff after deviation is

$$\bar{e} - n\bar{e} + (w_1 - \tau) - \varepsilon + \frac{(1-\beta)(\tau+\varepsilon)+\beta\overline{w}}{n}.$$

Here $n\bar{e} - (w_1 - \tau)$ is the amount by which the player must decrease her effort in order to have the resource at exactly τ before the growth. The comparison of on-the-path payoff with off-the-path payoff shows that the former is bigger or equal than the latter for the values of w_1 in this Case with equality holding when w_1 is the highest. Thus no profitable deviation is possible. One last possibility remains: the decrease in effort might be so big that the amount of the resource after the growth (w_2) might fall into the category of Case 4 below. This means that, according to the strategy in Case 4, the players will exert efforts so that not to exhaust the resource below τ in period 2 and will only exhaust it completely in period 3. This possibility, however, is prevented by the assumption in this Proposition ($n\tau < (n-1+\beta)\bar{e}$). To see this, let us find the lowest ε such that if the resource is equal to $\tau+\varepsilon$ before growth, it grows "into" the interval $[n\bar{e}+\tau-\frac{\beta(\overline{w}-\tau)}{n-1}, n\bar{e}+\tau]$ (as in Case 4). This smallest ε satisfies

$$(1-\beta)(\tau+\varepsilon)+\beta\overline{w} = n\bar{e}+\tau-\frac{\beta(\overline{w}-\tau)}{n-1}.$$

Rearrangement gives:

$$\varepsilon = \frac{n}{1-\beta}\left[\bar{e} - \frac{\beta(\overline{w}-\tau)}{n-1}\right] \geq \frac{n}{1-\beta}\left[\bar{e}-\tau\right] > \frac{(1-\beta)\bar{e}}{1-\beta} = \bar{e},$$

where the weak inequality follows from the first assumption of the Proposition and the strong one from the second. This implies that if on-the-path resource after the efforts is below τ, then no player can decrease her effort so that the resource after growth fall into Case 4.[6] Thus, we have shown that no deviation in this Case is possible.

Case 4: $w_1 \in (n\bar{e} + \tau - \frac{\beta(\overline{w}-\tau)}{n-1}, n\bar{e} + \tau)$.
In this Case the strategy in the Proposition prescribes to choose effort $\frac{w_1-\tau}{n}$ for all players, which will bring the resource before growth down to τ. On the path the payoff is

$$\frac{w_1 - \tau}{n} + \frac{(1-\beta)\tau + \beta\overline{w}}{n}.$$

Suppose a player increases her effort by ε. Then her new payoff is $\frac{w_1-\tau}{n} + \varepsilon + \frac{\tau-\varepsilon}{n}$. This increases in ε, thus we should consider the highest ε possible. Notice that $\frac{w_1-\tau}{n} \in (\bar{e} - \frac{\beta(\overline{w}-\tau)}{n(n-1)}, \bar{e})$. Thus, the highest possible ε is $\frac{\beta(\overline{w}-\tau)}{n(n-1)}$ (the limit). With this ε the on-the-path payoff is strictly higher than off-the-path one. Thus, no profitable deviation in the direction of increasing the effort is possible. The player can also decrease her effort. In this case after deviation she will get

$$\frac{w_1 - \tau}{n} - \varepsilon + \frac{(1-\beta)(\tau + \varepsilon) + \beta\overline{w}}{n}.$$

This decreases in ε. Therefore, no profitable deviation of this sort is possible. The one last possibility is that the decrease in effort is so big that after the growth the resource falls into Case 4 again, which leads to additional period of growth. However, this is impossible, since for this to happen ε should be higher than $\bar{e}$, as was shown in the previous Case. Therefore, no profitable deviation exists.

Case 5: $w_1 \in [n\bar{e} + \tau, \overline{w}]$.
The third assumption of the Proposition is $\overline{w} \leq (n + (n-1)(1-\beta))\bar{e}$. It guarantees that if $n-1$ players exert effort $\bar{e}$ and one exerts effort 0, then the amount of the resource after regrowth will be less than $n\bar{e}$. This assumption makes sure that, even starting from the top amount of the resource, one player cannot force the amount of the resource to fall into Case 4 in the next period (even if she exerts zero effort). Moreover, the same condition guarantees that $\overline{w} - n\bar{e} < n\bar{e}$, so that after all players, starting as high as the full resource, exert highest effort, the next period they will exhaust the resource (Cases 1 and 2). So, on the proposed equilibrium path the payoff is $\bar{e} + ((1-\beta)(w_1 - n\bar{e}) + \beta\overline{w})/n$. The deviation by one player in the direction of the reduction of the resource by ε gives $\bar{e} - \varepsilon + ((1-\beta)(w_1 - n\bar{e} + \varepsilon) + \beta\overline{w})/n$. The deviation payoff decreases in ε, thus no profitable deviation is possible.

The same proofs as in the five Cases above can be applied to any amount of the resource w_t in

[6] The SPNE fails if this is not true. The assumption $n\tau < (n-1+\beta)\bar{e}$ that is necessary for the result is not that much harsher than the assumption $\tau < \bar{e}$ that needs to be made for all the proofs and which is not that restrictive given that τ is thought of as a very small amount anyway.

any period $t = 1..L-1$. Thus we have SPNE. ■

* * *

Proposition 4. *The following choice procedure generates the solution to the Social Planner's problem (3) as long as $\tau < \bar{e}$. In periods $t = 1..L$, $e_t = \bar{e}$ if the resource before period t is $w_t \geq \bar{e} + \tau$. However, in period $t = 1..L-1$, $e_t = w_t - \tau$ if $w_t \in [\tau, \bar{e} + \tau)$ and $e_t = w_t$ if $w_t < \tau$. If $w_L < \bar{e} + \tau$ then $e_L = \min\{\bar{e}, w_L\}$.*

Proof of Proposition 4. We employ an induction argument on the sequence of value functions constructed by working backwards from the last period. Let us restate the maximization problem:

$$\begin{aligned} & \max_{(e_t)_{t=1..L}} \sum_{t=1}^{L} e_t \\ \text{s.t.} \quad & w_{t+1} = (1-\beta)(w_t - e_t) + \beta\overline{w} \\ & 0 \leq e_t \leq \min\{\bar{e}, w_t - \tau\} \quad \text{for} \quad t = 1..L-1 \\ & 0 \leq e_L \leq \min\{\bar{e}, w_L\}. \end{aligned}$$

Consider the value function which by Bellman's Principle of Optimality should characterize the solution in period L:

$$\begin{aligned} V_L(w) \quad &= \quad \max_e \;\; e \\ & \quad\;\; \text{s.t.} \quad 0 \leq e \leq \min\{\bar{e}, w\}. \end{aligned}$$

Obviously, $V_L(w) = \min\{\bar{e}, w\}$ which implies that $V_L(w) = \bar{e}$ if $w > \bar{e}$ and $V_L(w) = w$ if $w \leq \bar{e}$. Thus, V_L is a weakly increasing piecewise linear *continuous* function with slope 0 or 1.

Now consider the value function $V_{L-1} : [\tau, \overline{w}] \to \mathbb{R}$ for period $L-1$:

$$\begin{aligned} V_{L-1}(w) \quad &= \quad \max_e \;\; e + V_L(w') \\ & \quad\;\; \text{s.t.} \quad w' = (1-\beta)(w-e) + \beta\overline{w} \\ & \quad\;\; \phantom{\text{s.t.}} \quad 0 \leq e \leq \min\{\bar{e}, w - \tau\}. \end{aligned}$$

For any fixed w the maximand $e + V_L((1-\beta)(w-e) + \beta\overline{w})$ is an increasing piecewise linear continuous function of e because $V_L((1-\beta)(w-e) + \beta\overline{w})$ is a decreasing function of e with slopes $-(1-\beta)$ or 0. Thus, the solution to the maximization problem is given by the maximum e possible. Therefore, if $w \leq \bar{e} + \tau$, we have $V_{L-1}(w) = w - \tau + \min\{\bar{e}, (1-\beta)\tau + \beta\overline{w}\}$, and if $w > \bar{e} + \tau$, then $V_{L-1}(w) = \bar{e} + \min\{\bar{e}, (1-\beta)(w - \bar{e}) + \beta\overline{w}\}$. Plugging $w = \bar{e} + \tau$ into these two definitions we can easily see that V_{L-1} connects at $V_{L-1}(\bar{e} + \tau) = \bar{e} + \min\{\bar{e}, (1-\beta)\tau + \beta\overline{w}\}$. Since both definitions of V_{L-1} are weakly increasing we can conclude that V_{L-1} is *weakly increasing* continuous piecewise linear with slopes 1, 0 and possibly $1-\beta$ (if $\bar{e} > (1-\beta)(w - \bar{e}) + \beta\overline{w}$). Notice that the optimal e here is the same as described in this Proposition.

Now we are ready to formulate the induction argument. V_{L-2} is given by

$$\begin{aligned} V_{L-2}(w) &= \max_e \; e + V_{L-1}(w') \\ &\text{s.t. } \; w' = (1-\beta)(w-e) + \beta\overline{w} \\ &\qquad 0 \le e \le \min\{\bar{e}, w-\tau\}. \end{aligned}$$

Again, $e + V_{L-1}((1-\beta)(w-e)+\beta\overline{w})$ is an increasing function of e, thus the optimal e is the maximum one.[7] If $w \le \bar{e}+\tau$, we have $V_{L-2}(w) = w - \tau + V_{L-1}((1-\beta)\tau + \beta\overline{w})$, and if $w > \bar{e}+\tau$, then $V_{L-2}(w) = \bar{e} + V_{L-1}((1-\beta)(w-\bar{e}) + \beta\overline{w})$. Again, the two pieces of V_{L-2} connect at $V_{L-2}(\bar{e}+\tau) = \bar{e} + V_{L-1}((1-\beta)\tau + \beta\overline{w})$, and since both pieces are weakly increasing and continuous, we conclude that V_{L-2} is weakly increasing continuous piecewise linear with slopes: 1 (first piece) and some slopes that do not exceed $1-\beta$ (second piece).

Notice that in this argument we used only two properties of V_{L-1}: 1) that it is weakly increasing continuous; 2) that it is piecewise linear with slopes not exceeding 1. Thus, since we found that V_{L-2} enjoys both of these properties, the same argument can be used to show that for any $k > 2$

$$\begin{aligned} V_{L-k}(w) &= \max_e \; e + V_{L-k+1}(w') \\ &\text{s.t. } \; w' = (1-\beta)(w-e) + \beta\overline{w} \\ &\qquad 0 \le e \le \min\{\bar{e}, w-\tau\} \end{aligned}$$

is a weakly increasing continuous piecewise linear with slopes not exceeding 1. By the Principle of Optimality the sequence of functions $(V_t)_{t=1..L}$ characterizes the solution to the problem (4) and consecutively to the problem (3) if $\tau < \bar{e}$. This, in its turn, implies that choices of e_t are as described in the Proposition. ■

C Lemmata

Lemma 1. *For some fixed W suppose $c := \overline{w} - \frac{1-\beta}{\beta} n\bar{e} < W$ and $w_1 \ge W$. If in each period $k \ge 1$ all players exert effort $\bar{e}$ then there exists $M \in \mathbb{N}$ such that for all $k < M$, $w_k \ge W$ and for all $k \ge M$, $w_k < W$. Moreover, $M = 1 + \left\lceil \log_{1-\beta} \frac{W-c}{w_1-c} \right\rceil$.*

Proof. Suppose before period 1 the amount of the resource is w_1. If all players exert effort $\bar{e}$ then before period 2 the amount of resource will be

$$w_2 = (1-\beta)(w_1 - n\bar{e}) + \beta\overline{w} = (1-\beta)w_1 + \beta\left[\overline{w} - \frac{1-\beta}{\beta}n\bar{e}\right].$$

Analogously, if players continue exerting effort $\bar{e}$, the amount of resource at the beginning of pe-

[7] This is because the slopes of V_{L-1} do not exceed 1.

riod t will be

$$w_t = (1-\beta)w_{t-1} + \beta\left[\overline{w} - \frac{1-\beta}{\beta}n\bar{e}\right].$$

Let $c = \overline{w} - \frac{1-\beta}{\beta}n\bar{e}$. Then we can rewrite the difference equation above as $w_t = (1-\beta)w_{t-1} + \beta c$. This difference equation has a unique solution of the form

$$w_t = C(1-\beta)^t + c$$

where $C = \frac{w_1 - c}{1-\beta}$ depends on the initial conditions (in our case w_1). By assumption of the Lemma $C > 0$. It is clear that $\lim_{t\to\infty} w_t = c < W$. Therefore, there exists a period M such that $w_M < W$. Moreover, w_t is strictly decreasing sequence, thus the conditions of the Lemma are satisfied. To find M solve for t in $C(1-\beta)^t + c = W$. It gives

$$M = 1 + \left\lceil \log_{1-\beta}\frac{W-c}{w_1-c}\right\rceil.$$

The logarithm is well defined by the assumptions of the Lemma. ■

* * *

Lemma 2. *For any solution to Social Planner's problem (3):*

$$\begin{aligned} &\max_{(e_t)_{t=1..L}} \sum_{t=1}^{L} e_t \\ s.t.\quad & w_{t+1} = w_t - e_t + \beta(\overline{w} - (w_t - e_t))\mathbb{1}_{w_t - e_t \geq \tau} \\ & 0 \leq e_t \leq \min\{\bar{e}, w_t\} \end{aligned} \tag{13}$$

it is true that $w_t \geq \tau$ for all $t = 1..L-1$ whenever $w_1 \geq \tau$ and $\tau < \bar{e}$.

Proof. Suppose $(e_t)_{t=1..L}$ is a solution to the problem (3) and suppose that for some $k \leq L-1$ the size of the resource is $w_k \geq \tau$ and $w_{k+1} < \tau$. By condition (13) this implies that $w_t < \tau$ for all future periods $t > k+1$ as resource growth is not possible anymore. For any solution $(e_t)_{t=1..L}$, it will then be true that

$$\sum_{t=k+1}^{L} e_t = w_{k+1}$$

as "eating" less than that amount would be not optimal. This also implies that $\sum_{t=k}^{L} e_t = w_k$ (by (13)).

Suppose now that a player exerts effort $e_k = w_k - \tau$ instead of $w_k - w_{k+1}$ in period k and in period $k+1$ she consumes as much as possible: $\min\{\bar{e}, (1-\beta)\tau + \beta\overline{w}\}$. Then the payoff from period k on is at least $w_k - \tau + \min\{\bar{e}, (1-\beta)\tau + \beta\overline{w}\}$, which is $w_k + \bar{e} - \tau > w_k$ or $w_k + \beta(\overline{w} - \tau) > w_k$. In both cases this is higher than the original continuation payoff w_k. Therefore, it cannot be optimal to exert effort $w_k - w_{k+1}$ in period k reducing size of the resource below τ. ■

D Social Planner's Problem with a Positive Externality

In this section we consider a modified Social Planner's problem. We assume that preserving the resource above some level creates a positive externality. We assume that there is a level $\eta > \tau$ such that if in period t the resource is above η then society's utility in period t becomes $e_t + u$ where $u > 0$ represents the benefit to the society from having sufficient resource stock to satisfy non-harvesting individuals. Thus Social Planner's problem becomes:

$$\begin{aligned} &\max_{(e_t)_{t=1..L}} \sum_{t=1}^{L} e_t + u\mathbb{1}_{w_t \geq \eta} \\ \text{s.t.} \quad & w_{t+1} = w_t - e_t + \beta(\overline{w} - (w_t - e_t))\mathbb{1}_{w_t - e_t \geq \tau} \\ & 0 \leq e_t \leq \min\{\bar{e}, w_t\}. \end{aligned} \tag{14}$$

Since by assumption $\eta > \tau$, Lemma 2 applies to this maximization problem exactly as it did to the problem (3). Therefore, we can rewrite problem (14) as

$$\begin{aligned} &\max_{(e_t)_{t=1..L}} \sum_{t=1}^{L} e_t + u\mathbb{1}_{w_t \geq \eta} \\ \text{s.t.} \quad & w_{t+1} = (1-\beta)(w_t - e_t) + \beta\overline{w} \\ & 0 \leq e_t \leq \min\{\bar{e}, w_t - \tau\} \quad \text{for } t = 1..L-1 \\ & 0 \leq e_L \leq \min\{\bar{e}, w_L\}. \end{aligned} \tag{15}$$

Let $w^* = \frac{\eta - \beta\overline{w}}{1-\beta} + \bar{e}$ and $w_* = \frac{\eta - \beta\overline{w}}{1-\beta}$. Then the following Proposition characterizes the solution to problem (14).

Proposition 6. *Suppose that $\tau < w^* < \overline{w}$ and $\tau < w_*$.*[8] *The choice procedure that generates the optimal solution in problem (14) is the same as in problem (3) except that in each period $t = 1..L-1$ there exists a non-empty interval $[a_t, w^*]$ with $a_t \geq w_*$ such that $e_t = w_t - w_*$ for all $w_t \in [a_t, w^*]$.*

Proof. See below in this Appendix.

Notice that removing two assumptions of the Proposition ($\tau < w^* < \overline{w}$ and $\tau < w_*$) does not change the final conclusions regarding the optimal choice procedure. The only difference is that without these assumptions some parts of the proof become unnecessary.

Now we will characterize what happens on the optimal path of problem (14). Proposition 6 says that on the optimal path, maximal effort $\bar{e}$ or the effort that reduces the next period resource stock to $(1-\beta)\tau + \beta\overline{w}$ will be chosen in all periods with the exception of those periods in which

[8] These assumptions guarantee that the most general case of the problem is considered.

the previous period's resource stock lies in the interval $w_t \in [a_t, w^*]$. In these cases, effort is chosen so that the next period resource level is η. Since $(a_t)_{t=1..L-1}$ depend on the exact shapes of the value functions in each period, it is hard to provide an exact formula for each a_t. However, it is possible to estimate maximal values of a_t. Consider equation (18) from the proof:

$$v_{t-1}(w) = \max\left\{w - \frac{\eta - \beta\overline{w}}{1-\beta} + V_t(\eta), \bar{e} + V_t((1-\beta)(w-\bar{e}) + \beta\overline{w})\right\}.$$

It characterizes the continuous part of the value function in the interval of resource levels $w \in [w_*, w^*)$. We know from the proof that a_t is either the resource level where two functions inside the max operator intersect or is equal to w_*. Therefore, the minimum possible a_t is $w_* = w^* - \bar{e}$ and the maximum possible a_t is attained if $\bar{e} + V_t((1-\beta)(w-\bar{e}) + \beta\overline{w})$ is constant in w and intersects $w - \frac{\eta-\beta\overline{w}}{1-\beta} + V_t(\eta)$. Inequality (19) then shows that maximal a_t is $w^* - u$. Therefore, in any period t the length of the interval $[a_t, w^*]$ is $\min\{u, \bar{e}\}$.[9]

The length of the interval $[a_t, w^*]$ (in which the optimal choice is to harvest the resource so that the next period's resource stock is equal to η) is important for the optimal path that will be followed. If this interval is sufficiently small (e.g. if $u \to 0$), then the optimal path will be very similar to the path of problem (3). On the other hand, if the length is $\bar{e}$, then the optimal path will converge to η from some period until the end of the game as long as initial w_1 is big enough. To see this consider three cases.

Case $(1-\beta)\tau + \beta\overline{w} > \eta$ and $u > 0$

Here η is so small that even if the resource falls to the level τ, next period it will regrow to be larger than η. This implies that whatever the initial conditions are, the resource stock will *always* remain above η.

Case $(1-\beta)\tau + \beta\overline{w} \in [w_*, \eta]$ and $u \geq \bar{e}$

Here the optimal path will *either* reduce the resource level to η and remain there until the last period *or* will at some point exceed η and remain greater than η until the last period. Notice first that $u \geq \bar{e}$ implies that in any period the length of the interval $[a_t, w^*]$ is $\bar{e}$ (or $a_t = w_*$). Also notice that even if the resource falls to τ after some period it will grow to $(1-\beta)\tau + \beta\overline{w} \geq w_*$ next period thus necessitating the jump to η in the subsequent period.

If $\eta \in (w_*, w^*]$ then

$$(1-\beta)\tau + \beta\overline{w} \leq \eta \;\Leftrightarrow\; \eta - e^*(\eta) \geq \tau$$

where $e^*(\eta) = \eta - w_*$ is the optimal choice at η. This equivalence means that once the level of the resource is η, it will remain there since at this level, the optimal choice is feasible. The resource stock will always end up at level η at some point and the planner will continue to harvest so that it remains there. This is because: 1) for $w_1 \in [\tau, w_*)$, the next period resource level will be

[9] However, depending on the parameters it may be the case that w^* is very close to τ. In this case $a_t = \tau$ and the length of the interval is $w^* - \tau$. In interesting cases though we will have $a_t > \tau$ and the length will be $\min\{u, \bar{e}\}$.

$(1-\beta)\tau + \beta\overline{w} \in [w_*, \eta]$ and thus η in the subsequent period; 2) for $w_1 \in [w_*, w^*]$, the next period resource level will be η; 3) for $w_1 > w^*$ the resource level will eventually be reduced into the interval $(w_*, w^*]$ since

$$\eta \leq w^* \;\Leftrightarrow\; \eta \geq \overline{w} - \frac{1-\beta}{\beta}\bar{e} \;\Leftrightarrow\; w^* \geq \overline{w} - \frac{1-\beta}{\beta}\bar{e},$$

and $\overline{w} - \frac{1-\beta}{\beta}\bar{e}$ is the precise resource level such that, by exerting effort $\bar{e}$ above it, the planner will always reduce the next period resource level, so that it converges to $\overline{w} - \frac{1-\beta}{\beta}\bar{e}$ (see Lemma 1 with $n = 1$).

If $\eta > w^*$ then at some point, the resource level will increase above η and will remain above it until the final period. Indeed,

$$\eta > w^* \;\Leftrightarrow\; \eta < \overline{w} - \frac{1-\beta}{\beta}\bar{e}.$$

This means that for $w_1 \in [\tau, \eta]$ the resource stock will increase towards $\overline{w} - \frac{1-\beta}{\beta}\bar{e}$, necessarily passing through the interval $[w_*, w^*]$, since its length is $\bar{e}$. This implies that the resource stock will be equal to η at some point. Once η is reached, the optimal choice will be $e^*(\eta) = \bar{e}$. But by definition of w^* (see proof of Proposition 6) for any resource $w > w^*$ even if effort $\bar{e}$ is exerted, the next period resource level will be greater than η. Thus, since $\eta > w^*$ at some point, the resource level will always remain greater than η. Thus, for $w_1 > \eta > w^*$ the next period resource (and all others until the end) will remain above η for the same reason.

Case $(1-\beta)\tau + \beta\overline{w} < w_*$ and $u \geq \bar{e}$

In this case the resource level will either drop to $(1-\beta)\tau + \beta\overline{w}$ or behave as in the previous case. As before we have $a_t = w_*$ for all t and, since $(1-\beta)\tau + \beta\overline{w} < w_*$, if $w_1 \in [\tau, w_*)$ the resource will stay at level $(1-\beta)\tau + \beta\overline{w} < w_* < \eta$ until the end of the game (last inequality is true since $w_* < \eta \;\Leftrightarrow\; \eta < \overline{w}$ always holds).

If $\eta \in (w_*, w^*]$ then

$$(1-\beta)\tau + \beta\overline{w} < w_* \;\Rightarrow\; \eta - e^*(\eta) > \tau$$

where $e^*(\eta) = \eta - w_*$. Thus, as before, if resource falls into the interval $(w_*, w^*]$ it will stay at level η until last period. The rest of the argument for $\eta \in (w_*, w^*]$ and $\eta > w^*$ is the same as in the previous case excluding values $w_1 \in [\tau, w_*)$.

D.1 Proof of Proposition 6

Proof of Proposition 6. The proof follows the same logic as the proof of Proposition 4. Let us restate the maximization problem:

$$\begin{aligned} & \max_{(e_t)_{t=1..L}} \sum_{t=1}^{L} e_t + u\mathbb{1}_{w_t \geq \eta} \\ \text{s.t.} \quad & w_{t+1} = (1-\beta)(w_t - e_t) + \beta\overline{w} \\ & 0 \leq e_t \leq \min\{\bar{e}, w_t - \tau\} \quad \text{for} \quad t = 1..L-1 \\ & 0 \leq e_L \leq \min\{\bar{e}, w_L\}. \end{aligned}$$

The value function that characterizes the solution in period L is

$$\begin{aligned} V_L(w) \quad = \quad & \max_e \; e + u\mathbb{1}_{w \geq \eta} \\ \text{s.t.} \quad & 0 \leq e \leq \min\{\bar{e}, w\}. \end{aligned}$$

Clearly, $V_L(w) = \min\{\bar{e}, w\}$ for $w < \eta$ and $V_L(w) = \min\{\bar{e}, w\} + u$ for $w \geq \eta$. $V_L(w)$ is piecewise linear weakly increasing function with slopes 1 and 0 and with discontinuity at $w = \eta$. Let us write $V_L(w) = v_L(w) + u\mathbb{1}_{w \geq \eta}$ where $v_L(w) = \min\{\bar{e}, w\}$ is continuous "part" of V_L.[10] Notice that v_L is equal to the analogous function in the proof of Proposition 4. Therefore, the choice procedure prescribed by V_L is the same as in Proposition 4 ($u\mathbb{1}_{w \geq \eta}$ doesn't play any role here).

Consider now the value function $V_{L-1} : [\tau, \overline{w}] \to \mathbb{R}$ for period $L-1$:

$$\begin{aligned} V_{L-1}(w) \quad = \quad & \max_e \; e + u\mathbb{1}_{w \geq \eta} + V_L(w') \\ \text{s.t.} \quad & w' = (1-\beta)(w - e) + \beta\overline{w} \\ & 0 \leq e \leq \min\{\bar{e}, w - \tau\}. \end{aligned}$$

Here $u\mathbb{1}_{w \geq \eta}$ is constant for each given w. Therefore, the function

$$\begin{aligned} v_{L-1}(w) \quad = \quad & \max_e \; e + V_L(w') \\ \text{s.t.} \quad & w' = (1-\beta)(w - e) + \beta\overline{w} \\ & 0 \leq e \leq \min\{\bar{e}, w - \tau\}. \end{aligned} \tag{16}$$

is a candidate for the continuous part of V_{L-1}.

Now we will show two things simultaneously: 1) that v_{L-1} is continuous and 2) that optimal choices of effort for different w correspond to those described in this Proposition. Consider first the levels of the resource w satisfying $(1-\beta)(w - \bar{e}) + \beta\overline{w} \geq \eta$. We can rearrange this to get

[10] The notation $V_t(w) = v_t(w) + u\mathbb{1}_{w \geq \eta}$ will be used throughout the proof.

$w \geq \frac{\eta-\beta\overline{w}}{1-\beta} + \bar{e} = w^*$.[11] For all these levels $w \geq w^*$ it is true that if w is the amount of the resource before period $L-1$, then, even if maximal effort $\bar{e}$ is exerted, in period L the amount of the resource will be higher than η. This implies that $V_L(w) = v_L(w) + u$ for all $w \geq w^*$ in problem (16). This in turn means that for all $w \geq w^*$ the optimal choices of effort will coincide with analogous choices in the proof of Proposition 4: all that changes is added constant u. Moreover, $v_{L-1}(w)$ restricted to $w \geq w^*$ is continuous by Proposition 4.

Using the same argument, consider levels of the resource w such that $(1-\beta)w + \beta\overline{w} < \eta$. These levels w are such that even if no effort is exerted in the current period, next period the amount of the resource will be less than η. We can rewrite this as $w < \frac{\eta-\beta\overline{w}}{1-\beta} = w_*$.[12] For all $w \in [\tau, w_*)$ it is then true that $V_L(w) = v_L(w)$. Thus, for all $w \in [\tau, w_*)$ the optimal choices are the same as in the analogous problem in Proposition 4. Moreover, v_{L-1} restricted to $w \in [\tau, w_*)$ is continuous by Proposition 4.

Now let us find optimal choices for $w \in [w_*, w^*)$. First, consider the maximand function $e + V_L(w')$ in (16) when $w = w^*$. For $w = w^*$, w' ranges in the interval $[\eta, (1-\beta)w^* + \beta\overline{w}]$ as e changes from 0 to $\bar{e}$.[13] Thus, $e + V_L((1-\beta)(w^*-e) + \beta\overline{w})$ is a continuous, strictly increasing function of e as V_L restricted to $[\eta, (1-\beta)w^* + \beta\overline{w}]$ is weakly increasing with slopes no more than 1 and continuous. Now let us perform the same analysis for $w = w^* - \varepsilon$ where ε is sufficiently small positive number. For $w = w^* - \varepsilon$, w' ranges in the interval $[\eta - (1-\beta)\varepsilon, (1-\beta)w^* + \beta\overline{w} - (1-\beta)\varepsilon]$ as e changes. Thus, the maximand function

$$m(e;\varepsilon) = e + V_L((1-\beta)(w^* - \varepsilon - e) + \beta\overline{w}) \tag{17}$$

increases strictly and continuously as e goes from 0 to $\bar{e} - \varepsilon$, then has a discontinuous drop of size $(1-\beta)u$, and then increases again strictly and continuously as e goes from $\bar{e} - \varepsilon$ to $\bar{e}$.[14] Given ε small enough the optimal effort choice will be at $e^* = \bar{e} - \varepsilon$ or such that $(1-\beta)(w^* - \varepsilon - e^*) + \beta\overline{w} = \eta$ which gives $e^* = w^* - \varepsilon - \frac{\eta-\beta\overline{w}}{1-\beta} = w - \frac{\eta-\beta\overline{w}}{1-\beta}$ as described in the Proposition. More importantly though, this argument shows the *existence* of an interval $[a_{L-1}, w^*)$ of levels of the resource (some range of small enough ε) such that $e^* = w - \frac{\eta-\beta\overline{w}}{1-\beta}$ for all $w \in [a_{L-1}, w^*)$. Notice that this implies that effort e^* in this interval is chosen so that the amount of the resource before period L is exactly η. It is also easy to observe that $v_{L-1}(w)$ is continuous on the interval $(w^* - \varepsilon, w^* + \varepsilon)$ as $\lim_{\varepsilon\to 0} e^* = \bar{e}$.

Before continuing let us make an observation about the function $m(e;\varepsilon)$. It consists of two increasing continuous functions with a discontinuous drop at $e = \bar{e} - \varepsilon$. This implies that the

[11] Such w's might not exist for some combination of the parameters. However, in this Proposition we assume that they do ($\tau < w^* < \overline{w}$). This is in order to consider the most general case.

[12] Again, by the assumption made in this Proposition such $w's$ exist.

[13] By the assumption of this Proposition $\tau < w_* = w^* - \bar{e}$. Thus, at $w = w^*$ it is possible to exert full effort $\bar{e}$ resulting in $w' = \eta$ for $e = \bar{e}$.

[14] The last claim is due to the fact that $V_L(w)$ is weakly increasing and continuous with slopes no more than 1 for $w < \eta$.

maximum of $m(e;\varepsilon)$ can occur in only two places: at $e = \bar{e} - \varepsilon$ or at $e = \bar{e}$. As shown above, this implies that for $w = w^* - \varepsilon$ we have either $e^* = w - \frac{\eta - \beta\overline{w}}{1-\beta}$ or $e^* = \bar{e}$ on the interval $w \in [w_*, w^*)$. Thus we can rewrite $v_{L-1}(w)$ on $w \in [w_*, w^*)$ as

$$v_{L-1}(w) = \max\left\{w - \frac{\eta - \beta\overline{w}}{1-\beta} + V_L(\eta), \bar{e} + V_L((1-\beta)(w-\bar{e}) + \beta\overline{w})\right\}. \tag{18}$$

It is easy to see that $v_{L-1}(w)$ is the maximum of two continuous functions in w where the left function has slope 1 and the right function has slope no more than $1-\beta$. Moreover,

$$\begin{aligned} \lim_{w\uparrow w^*} w - \frac{\eta - \beta\overline{w}}{1-\beta} + V_L(\eta) &= \bar{e} + v_L(\eta) + u \quad > \\ > \lim_{w\uparrow w^*} \bar{e} + V_L((1-\beta)(w-\bar{e}) + \beta\overline{w}) &= \bar{e} + v_L(\eta) \end{aligned} \tag{19}$$

Thus, as w goes to w_* the function $w - \frac{\eta - \beta\overline{w}}{1-\beta} + V_L(\eta)$ may intersect the function $\bar{e} + V_L((1-\beta)(w - \bar{e}) + \beta\overline{w})$.[15] If the functions intersect, then we define a_{L-1} as the resource level at the intersection. Below a_{L-1} the optimal choice is $\bar{e}$. If the functions do not intersect then we define $a_{L-1} = w_*$ since we know from the above that below w_* the optimal choices are like in Proposition 4. The alternative representation, (18) also makes it easy to see that v_{L-1} is continuous at a_{L-1} whichever way it is defined.

Combining the above observations, we can conclude that $v_{L-1}(w)$ is a weakly increasing, piecewise linear continuous function. To complete the argument, we must show that the slopes of v_{L-1} do not exceed 1. Indeed, we showed that this is the case for $w \geq w^*$ and $w \in [\tau, a_{L-1})$. On the interval $[a_{L-1}, w^*]$ we have $v_{L-1}(w) = w - \frac{\eta - \beta\overline{w}}{1-\beta} + V_L(\eta)$ which has slope 1.

Since $v_{L-1}(w)$ is a weakly increasing and continuous with slopes no more than 1, we can conclude that $V_{L-1}(w)$ takes the same form, apart from the discontinuity at $w = \eta$. Thus, $V_{L-1}(w)$, as well as $V_L(w)$, is weakly increasing and continuous with slopes no more than 1 with discontinuity at $w = \eta$. In the proof above only these properties of $V_L(w)$ were used. Therefore, by induction, all the functions $V_1(w), V_2(w), ...V_{L-2}(w)$ have similar characteristics and optimal choices. ■

E Model with Norms

In this Appendix we construct SPNE for the model with norms presented in Section 2.4. We consider two models with the following parameters: $\overline{w} = 360$, $\bar{e} = 60$, $n = 4$; $\beta_H = 0.5$, $\beta_L = 0.25$, $\tau = 30$, $\alpha = 2$, $L = 10$. In all proofs below we do not look at cases when the resource amount is higher than $n\bar{e} + \tau = 270$, as these proofs are the same as in Propositions 2 and 3.

[15] Whether this intersection occurs depends on the parameters.

E.1 4 Rule-breakers

We would like to construct a SPNE in which rule-followers choose Social Planner's solution in all information sets and rule-breakers choose $\bar{e}$ in all information sets (but some with resource close to $n\bar{e} + \tau$ as in Proposition 3). First, notice that for resource levels $K \leq n\bar{e} = 240$ we want all players to choose $\bar{e}$ in accordance with the desired equilibrium. Second, for K small enough a player cannot decrease her effort in order to keep the resource at τ if other three players exert effort $\bar{e}$. The resource levels K for which this is true satisfy $n\bar{e} - K + \tau > \bar{e}$ or $K < 210$. The LHS of this expression is the amount by which one player should decrease her effort to have amount τ of the resource remain. Thus, for all $K < 210$ there is no deviation in which the resource grows afterwards. A player might be able to sustain the smaller than τ amount of the resource, but this will not be profitable, since in the next period the leftovers will be split equally among all players. Thus, choosing $\bar{e}$ for $K < 210$ is optimal (in any period).

Now we will construct best responses for $K \in [210, 240]$. Suppose in equilibrium all players choose $\bar{e}$ when $K \in [210, 240]$. Then

	on the path:	best deviation:
	$\frac{K}{4}$	$K - 3\bar{e} - \tau + \frac{1}{4}\left[\tau + \beta(\overline{w} - \tau)\right]$
	0	$3K - 12\bar{e} - 3\tau + \beta(\overline{w} - \tau)$
β_L :	0	$3 \cdot [210, 240] - 720 - 90 + 82.5 < 0$ for all K
β_H :	0	$3 \cdot [210, 240] - 720 - 90 + 165 < 0$ for $K < 215$.

Thus, in case of β_L it is optimal to choose $\bar{e}$ when $K \in [210, 240]$. $K > 240$ cases 3, 4, 5 of Proposition 3 show that there are no profitable deviations from choosing $\bar{e}$.

In case of β_H it is optimal to choose $\bar{e}$ if $K < 215$. If $K \in [215, 270]$ then it is optimal to choose the amount that depletes the resource to τ:

on the path:	best deviation:
$\frac{K-\tau}{4} + \frac{1}{4}\left[\tau + \beta_H(\overline{w} - \tau)\right]$	maximum $\frac{K-\tau}{4} + \tau$
$\frac{1}{4}\left[\tau + \beta_H(\overline{w} - \tau)\right]$	maximum τ
48.75	30.

Thus, it is optimal to jump to τ. The cases $K > 270$ are covered in Proposition 2.

Notice that $\tau + \beta_H(\overline{w} - \tau) = 195$ and $\tau + \beta_L(\overline{w} - \tau) = 112.5$. Both values are less than 210. So, once the resource is depleted to τ, next period after growth it will be exhausted in both cases. On equilibrium path in the game with low growth the resource will be 360, 180, 0. On the equilibrium path in the game with high growth the resource will be 360, 240, 195, 0.

E.2 3 Rule-breakers

Again we would like rule-followers to choose Social Planner's solution in equilibrium and rule-breakers to choose $\bar{e}$ whenever possible. When there are three rule-breakers and one rule-follower, rule-breakers can deplete the resource K if $K - \frac{1}{4}(K-\tau) \leq 3\bar{e}$ or $K \leq 230$ (LHS is how much of K is left after rule-follower chose). For some small enough K no rule-breaker will be able to decrease her effort to bring the resource to τ. Such K satisfies $\frac{1}{4}(K-\tau) + 3\bar{e} - K + \tau > \bar{e}$ or $K < 190$. Thus, for $K < 190$ it is optimal to exert full effort. For $K \in [190, 230]$ we have

$$
\begin{array}{lc|l}
 & \text{on the path:} & \text{best deviation:} \\
 & \frac{K - \frac{1}{4}(K-\tau)}{3} & K - \frac{1}{4}(K-\tau) - 2\bar{e} - \tau + \frac{1}{3}\left[(1-\beta)\tau + \beta\overline{w} - \frac{1}{4}\beta(\overline{w}-\tau)\right] \\
 & 0 & \frac{2}{3}(K - \frac{1}{4}(K-\tau)) - 2\bar{e} - \tau + \frac{1}{3}\left[(1-\beta)\tau + \beta\overline{w} - \frac{1}{4}\beta(\overline{w}-\tau)\right] \\
\beta_L: & 0 & [100, 120] - 120 - 30 + 30.625 < 0 \text{ for } K < 228.75 \\
\beta_H: & 0 & [100, 120] - 120 - 30 + 51.25 > 0 \text{ for all } K
\end{array}
$$

So equilibrium in the game with β_H where rule-breakers choose $\bar{e}$ for $K \in [190, 230]$ does not exist. For β_L it is optimal to choose $\bar{e}$ for $K \in [190, 228.75]$. For higher K it is easier to decrease effort to bring the resource to τ, thus for $K \in [228, 270]$ we need to check if doing it is optimal. For β_H this is indeed true by Proposition 2 (assuming rule-breakers follow the strategy described in the proposition). For β_L:

$$
\begin{array}{l|l}
\text{on the path:} & \text{best deviation:} \\
\frac{1}{4}(K-\tau) + \frac{1}{3}\left[(1-\beta_L)\tau + \beta_L\overline{w} - \frac{1}{4}\beta_L(\overline{w}-\tau)\right] & \text{maximum } \frac{1}{4}(K-\tau) + \tau \\
\frac{1}{3}\left[(1-\beta_L)\tau + \beta_L\overline{w} - \frac{1}{4}\beta_L(\overline{w}-\tau)\right] & \text{maximum } \tau \\
30.625 & 30
\end{array}
$$

Again, the cases $K > 270$ are covered in Propositions 2 and 3. Thus in high growth rate game rule-breakers choose $\bar{e}$ when $K < 190$ and choose to jump to τ for higher K. For low growth rate rule-breakers choose $\bar{e}$ when $K < 228.75$ and choose to jump to τ for higher K.

Now we need to calculate for which u the rule-follower is optimally choosing the Social Planner's solution. This should be checked only for K when rule-breakers choose $\bar{e}$ and rule-follower is able to decrease her effort to bring the resource to τ (else no profitable deviation exists). For high growth rate there is nothing to check since for $K \geq 190$ rule-breakers jump to τ and equilibrium works without any u (so $u = 0$). For the low growth rate we have an interval $K \in [190, 228.75]$ which needs to be checked:

$$
\begin{array}{l|l}
\text{on the path:} & \text{best deviation:} \\
\frac{1}{4}(K-\tau) + u & \text{maximum } \bar{e} \\
u & \text{maximum } 20
\end{array}
$$

So for $u \geq 20$ the rule-follower does not want to deviate from jumping to τ.

E.3 2 Rule-breakers

We would like rule-followers to choose Social Planner's solution in equilibrium and rule-breakers to choose $\bar{e}$ whenever possible. When there are two rule-breakers and two rule-followers, rule-breakers can deplete the resource K if $K - \frac{1}{2}(K-\tau) \leq 2\bar{e}$ or $K \leq 210$ (LHS is how much of K is left after rule-followers choose). For some small enough K no rule-breaker will be able to decrease her effort to bring the resource to τ. Such K satisfies $\frac{1}{2}(K-\tau) + 2\bar{e} - K + \tau > \bar{e}$ or $K < 150$. Thus, for $K < 150$ it is optimal to exert full effort. For $K \in [150, 210]$ we have

	on the path:	best deviation:
	$\frac{K-\frac{1}{2}(K-\tau)}{2}$	$K - \frac{1}{2}(K-\tau) - \bar{e} - \tau + \frac{1}{2}\left[(1-\beta)\tau + \beta\overline{w} - \frac{1}{2}\beta(\overline{w}-\tau)\right]$
	0	$\frac{1}{2}(K - \frac{1}{2}(K-\tau)) - \bar{e} - \tau + \frac{1}{2}\left[(1-\beta)\tau + \beta\overline{w} - \frac{1}{2}\beta(\overline{w}-\tau)\right]$
β_L :	0	$[45, 60] - 60 - 30 + 35.625 < 0$ for $K < 187.5$
β_H :	0	$[45, 60] - 60 - 30 + 56.25 > 0$ for all K

So equilibrium in the game with β_H where rule-breakers choose $\bar{e}$ for $K \in [150, 210]$ does not exist. For β_L it is optimal to choose $\bar{e}$ for $K \in [150, 187.5]$. For higher K it is easier to decrease effort to bring the resource to τ, thus for $K \in [187, 270]$ we need to check if doing it is optimal. For β_H this is indeed true by Proposition 2 (assuming rule-breakers follow the strategy described in the proposition). For β_L:

on the path:	best deviation:
$\frac{1}{4}(K-\tau) + \frac{1}{2}\left[(1-\beta)\tau + \beta\overline{w} - \frac{1}{2}\beta(\overline{w}-\tau)\right]$	maximum $\frac{1}{4}(K-\tau) + \tau$
$\frac{1}{2}\left[(1-\beta)\tau + \beta\overline{w} - \frac{1}{2}\beta(\overline{w}-\tau)\right]$	maximum τ
35.625	30

Thus in high growth rate game rule-breakers choose $\bar{e}$ when $K < 150$ and choose to jump to τ for higher K. For low growth rate rule-breakers choose $\bar{e}$ when $K < 187.5$ and choose to jump to τ for higher K.

Now we need to calculate for which u the rule-followers are optimally choosing the Social Planner's solution. This should be checked only for K when rule-breakers choose $\bar{e}$ and rule-follower is able to decrease her effort to bring the resource to τ (else no profitable deviation exists). For high growth rate there is nothing to check since for $K \geq 150$ rule-breakers jump to τ and equilibrium works without any u (so $u = 0$). For the low growth rate we have an interval $K \in [150, 187.5]$ which needs to be checked:

on the path:	best deviation:
$\frac{1}{4}(K-\tau) + u$	maximum $\bar{e}$
u	maximum 30

So for $u \geq 30$ the rule-follower does not want to deviate from jumping to τ.

E.4 1 Rule-breaker

We would like rule-followers to choose Social Planner's solution in equilibrium and rule-breakers to choose $\bar{e}$ whenever possible. When there is one rule-breaker and three rule-followers, rule-breaker can deplete the resource K if $K - \frac{3}{4}(K-\tau) \leq \bar{e}$ or $K \leq 150$. For some small enough K rule-breaker will not be able to decrease her effort to bring the resource to τ. Such K satisfies $\frac{3}{4}(K-\tau) + \bar{e} - K + \tau > \bar{e}$ or $K < 30$. For $K < 30$ it is already optimal to exert full effort because the resource does not replenish. For $K \in [30, 150]$ we have

$$\begin{array}{l|l} \text{on the path:} & \text{best deviation:} \\ K - \frac{3}{4}(K-\tau) & K - \frac{3}{4}(K-\tau) - \tau + \left[(1-\beta)\tau + \beta\overline{w} - \frac{3}{4}\beta(\overline{w}-\tau)\right] \\ 0 & -\tau + \left[(1-\beta)\tau + \beta\overline{w} - \frac{3}{4}\beta(\overline{w}-\tau)\right] \\ 0 & \frac{1}{4}\beta(\overline{w}-\tau) > 0 \text{ for all } K \end{array}$$

Thus, regardless of the growth rate, there is no equilibrium in which the rule-breaker chooses $\bar{e}$ when $K \in [30, 150]$. For higher K the deviation to make resource equal to τ is even easier. So we need to construct an equilibrium where rule-breaker jumps to τ when $K \in [30, 270]$. We have:

$$\begin{array}{l|l} \text{on the path:} & \text{best deviation:} \\ \frac{1}{4}(K-\tau) + \left[(1-\beta)\tau + \beta\overline{w} - \frac{3}{4}\beta(\overline{w}-\tau)\right] & \text{maximum } \frac{1}{4}(K-\tau) + \tau \\ \frac{1}{4}\beta(\overline{w}-\tau) & 0 \end{array}$$

So it is optimal for the rule-breaker to jump to τ in $K \in [30, 270]$ for both growth rates.

It is left to see which u makes the rule-followers stick to the Social Planner's solution. Since rule-breaker always jumps to τ when $K \geq 30$ Proposition 2 does the job for the high growth rate. For the low growth rate we need:

$$\text{for } K = 30 \text{ and } L = 1 \quad \begin{array}{l|l} \text{on the path:} & \text{best deviation:} \\ \frac{1}{4}(K-\tau) + (L-1)\frac{1}{4}\beta(\overline{w}-\tau) + Lu & \text{maximum } \bar{e} + \frac{\tau}{4} \\ & \\ u & \text{maximum } 67.5 \end{array}$$

Thus, if $u \geq 67.5$ then the rule-followers do not want to deviate from the SP's solution.

E.5 0 Rule-breakers

For the case of high growth rate there is nothing to show. Rule-followers will stick to the Social Planner's solution by Proposition 2. For the low growth rate we need to find u for which the rule-followers do not want to deviate from SP's solution to exhausting of the resource. The condition is the same as in the case of one rule-breaker, who jumps to τ. Thus, for $u \geq 67.5$ the rule-followers will stick to the SP's solution.

F Additional Experimental Findings

F.1 Histograms of Waiting Times

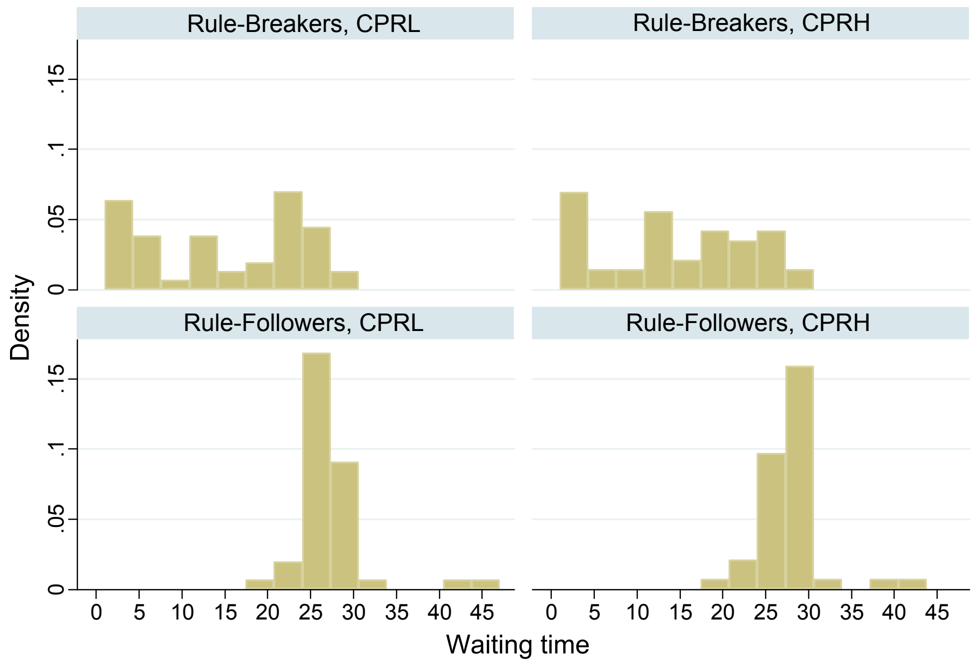

Figure F1: Histograms of total waiting time in RF task by group type in CPRL and CPRH treatments.

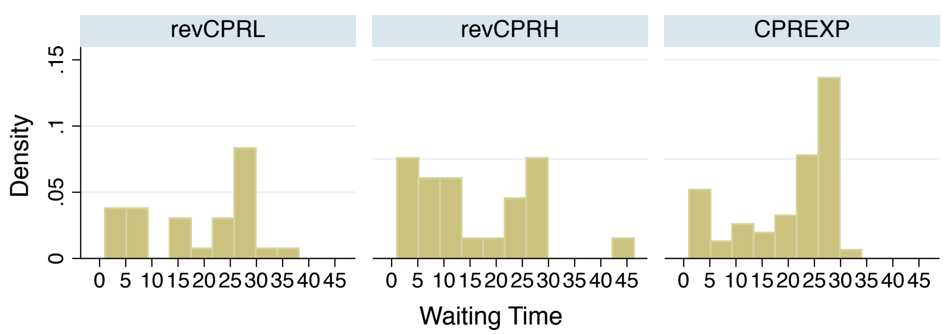

Figure F2: Histograms of total waiting time in RF task in revCPRL, revCPRH, and CPREXP treatments.

F.2 Regression Analysis of Individual Harvesting Decisions

The model in Section 2.4 suggests an explanation for the many cases in which CPRH groups deplete the resource despite favorable ecological conditions for resource sustainability. In the model, rule-followers receive additional utility from following a prescriptive social norm defined by the Social Planner's solution. There exist equilibria in which groups of rule-breakers will tend to over-harvest the resource while groups of rule-followers will aim to preserve it.

In particular, the model makes predictions about the behavior of both types when the resource is in danger of being depleted below the τ threshold. Rule-breakers will tend to choose the maximum possible harvest level to maximize their share of the pie, while rule-followers will attend to extract $\frac{w_t - \tau}{4}$. In the paper, we show that there is a negative relationship between the number of rule-breakers in a group and the period in which the resource is exhausted. Here we test the more subtle predictions of the model with regression analysis.

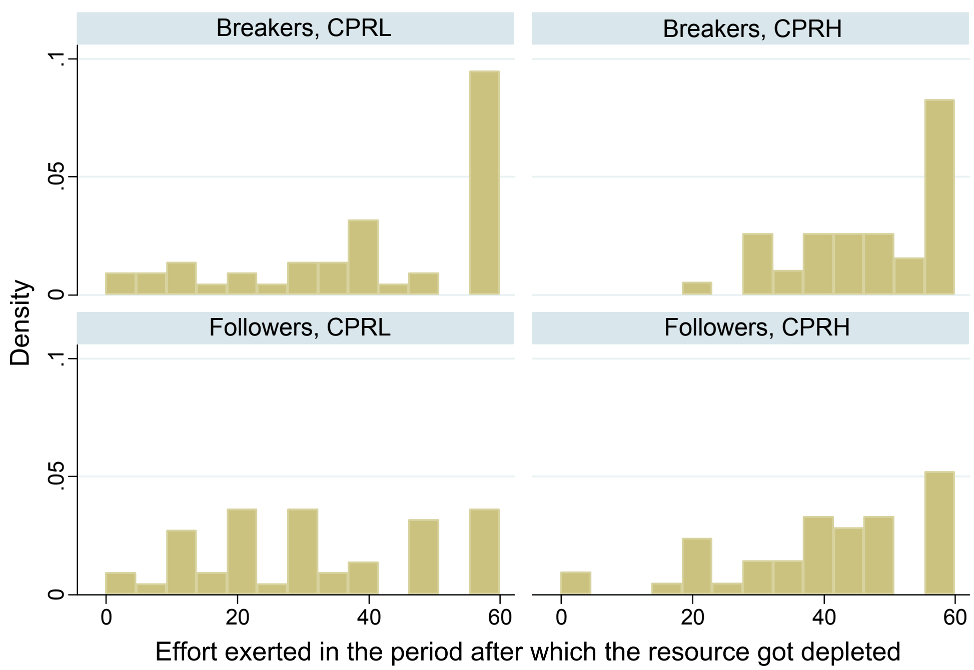

Figure F3: Histograms of the efforts exerted in the period right before the exhaustion of the resource by rule-breakers (waited less than 25 seconds in the RF task) and rule-followers (waited more than 25 seconds) in CPRH and CPRL treatments.

Figure F3 shows the efforts exerted by subjects in the period in which the resource was depleted below τ. Regardless of the treatment, there are many more rule-breakers who exert full effort than rule-followers. Table F1 reports regression analysis of these data. Independent variables are dummies for being a rule-follower (waited longer than 25 seconds in the RF task) and treatment (CPRH) and their interaction. The regression shows that rule-followers exert much less effort than rule-breakers in the period in which the resource is exhausted.Notice that rule-followers harvest around 8 tokens less than rule-breakers, which, when multiplied by 4, the number of players in the group, becomes 32 tokens which is very close to the value of τ. This suggests that rule-followers try to follow the SPNE in which the resource is harvested to τ in each period. The significant treatment dummy is due to the difference in the growth rate; the resource stock is larger in CPRH.

OLS: Effort	1	2	3	4
	β/se	β/se	β/se	β/se
CPRH	7.458***		7.648***	6.690*
	(2.718)		(2.395)	(3.343)
Follower		–8.182***	–8.356***	–9.250***
		(2.372)	(2.240)	(3.392)
CPRH×Follower				1.871
				(4.444)
const	37.042***	44.789***	41.219***	41.667***
	(2.219)	(1.845)	(2.521)	(2.978)
N	184	184	184	184

Table F1: OLS regression of effort exerted in the period before the resource drops below τ (or last period) in CPRH and CPRL treatments. Each observation is individual choice. Errors are clustered by group. *, **, *** are 10%, 5%, 1%.

F.3 Time Series of Resource Stocks by Session

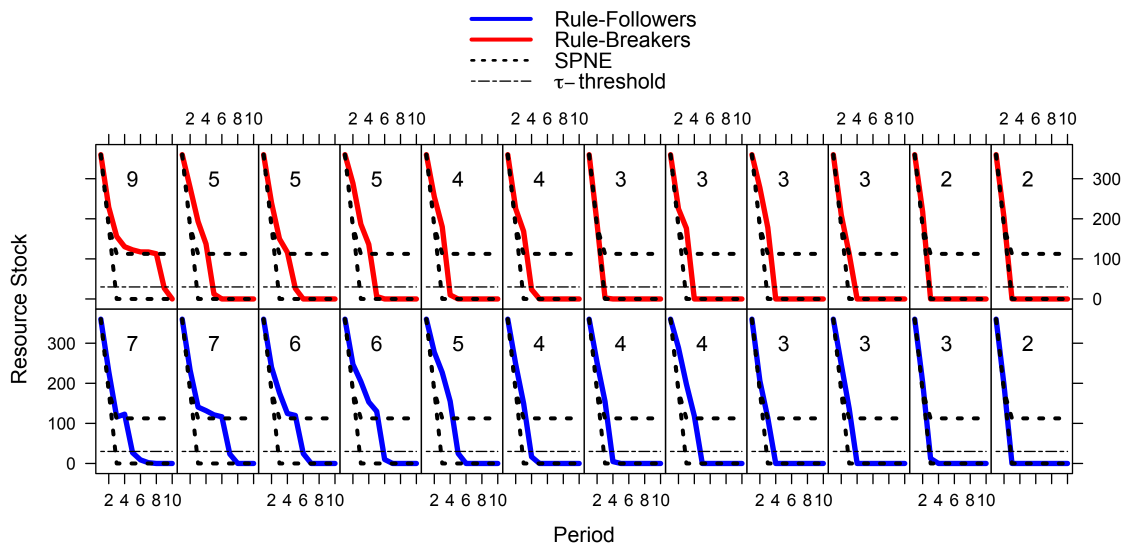

Figure F4: Time series of resource stocks by group in the CPRL treatment. The top row shows rule-breaking groups, and the bottom row shows rule-following groups. The numbers in the middle of each panel indicate the period in which the group exhausted the resource stock (`exhaustion`). The two SPNE plotted correspond to the equilibrium without norms and to the equilibrium with norms with 4 rule-breakers (in CPRH case) and 1 or 0 rule-breakers (in CPRL case).

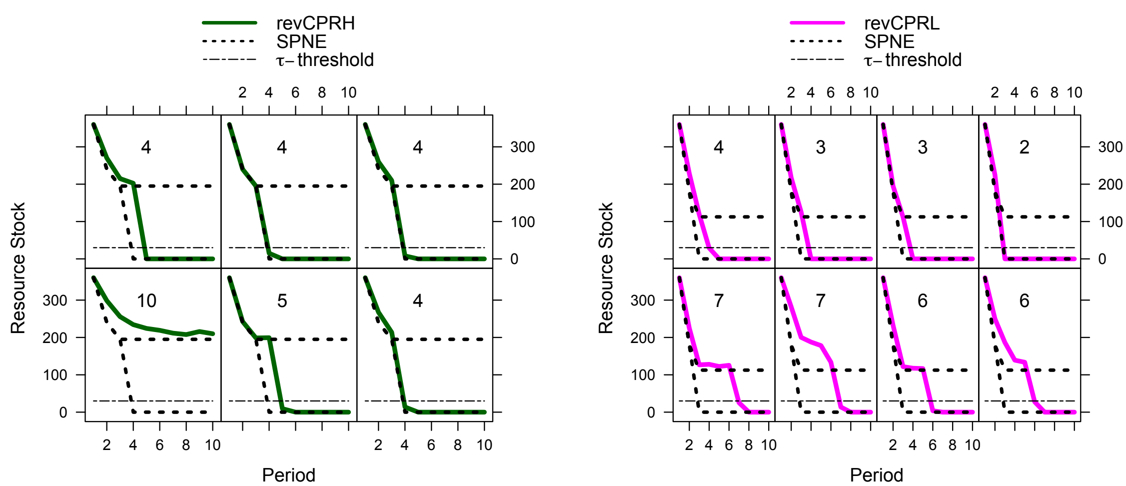

Figure F5: Time series of resource stocks in the reverse treatments. The two SPNE plotted correspond to the equilibrium without norms and to the equilibrium with norms with 4 rule-breakers (in CPRH case) and 1 or 0 rule-breakers (in CPRL case).

F.4 Exponential Growth Treatment

As an additional control, we explore how resource dynamics depend on the particular choice of resource regeneration function. In the 4 treatments discussed in this article, the resource regeneration function was proportional to the deviation from resource capacity so that the resource grew from level w, after harvesting choices were made in period t, to $w + \beta(\overline{w} - w)$ at the beginning of period $t + 1$. Thus, growth is high for low stocks of the resource and is vanishing as the resource converges to $\overline{w}$.[16] We wanted to see how group dynamics would change when we instead introduced an exponential growth function, where total capacity is unbounded. We substituted the "concave" growth above by "convex" one: $w \to w + \frac{w}{2}$. This growth function has the opposite properties: growth is low for low levels of the resource and high for high levels, and we refer to this as the CPREXP treatment.

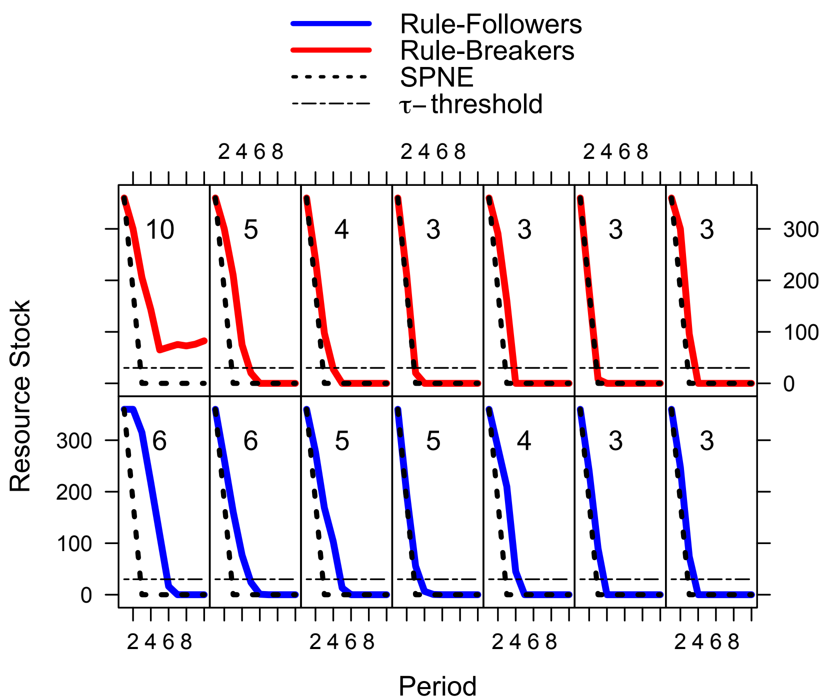

Figure F6: Time series of resource stocks in the CPREXP treatment, for Rule-followers and Rule-Breakers.

Here, rule-followers wait an average of 26.4 seconds during the RF task, while rule-breakers wait 13.6 seconds on average. Figure F6 displays time series of resource stocks for both rule-followers and rule-breakers in the CPREXP treatment, and a permutation test cannot reject the null hypothesis of equal period of `exhaustion` (means are 4.7 and 4.9 for rule-followers and rule-

[16]This type of growth is inherent to many natural systems, for example, populations of fish. When the fish population is small, there is plenty of food available and population grows very fast. As the population gets very large the growth stops, since there are natural limits on the amount of food available.

breakers, respectively, p-value $= 0.53$). Both rule-following and rule-breaking groups in CPREXP treatment exhaust the resource in about the same number of periods as groups in CPRL treatment, and permutation tests cannot reject the null hypothesis of equal mean period of `exhaustion` when comparing either rule-followers or rule-breakers across the treatments (p-values = 1.00 and 0.78, two-sided tests). As was discussed above, CPRL groups exhaust the resource relatively quickly because of the lower growth rate as compared to the CPRH treatment. This problem is more pronounced in the CPREXP treatment since the growth rate declines with the resource stock. Thus, we find that rule-followers in the CPREXP treatment exhaust the resource more quickly than their counterparts in the CPRH treatment (two-sided permutation test, p-value = 0.02). Rule-breakers on the other hand show no significant differences (p-value = 0.52, two-sided test).

F.5 Regression of Waiting Time on Individual Characteristics

	(1) Total Waiting Time
Female	3.450**
	(1.624)
Age	0.331
	(0.448)
Harm	-0.121
	(0.209)
Fairness	0.0165
	(0.231)
In-group	0.198
	(0.225)
Purity	0.0374
	(0.212)
Authority	0.144
	(0.218)
Economics	0.807
	(2.690)
Law	-9.188*
	(5.031)
Psychology	-1.152
	(3.100)
Other Major	-1.664
	(1.702)
Non-European	-0.0995
	(2.293)
Years of Study	0.446
	(0.675)
Reverse	-4.030
	(3.503)
Reverse $*$ # of times showing `restraint`	0.208 (1.051)
Reverse $*$ # of times others showed `restraint`	-0.364 (0.968)
Exponential	-2.382
	(1.961)
Constant	-642.0
	(892.4)
R^2	0.066
N	296

Standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table F2: OLS regression of total waiting time on individual characteristics. We also include controls for the Reverse and Exponential treatments, and in the reverse treatment we control for subjects' observed behavior, where `restraint` takes a value of 1 when a subject extracted less than his/her share in equilibrium, and others' `restraint` takes a value of 1 when others harvested less then their share.

G Instructions for the Rule Following Stage

General information

You are now participating in a decision making experiment. If you follow the instructions carefully, you can earn a considerable amount of money depending on your decisions and the decisions of the other participants. Your earnings will be paid to you in CASH at the end of the experiment

This set of instructions is for your private use only. **During the experiment you are not allowed to communicate with anybody**. In case of questions, please raise your hand. Then we will come to your seat and answer your questions. Any violation of this rule excludes you immediately from the experiment and all payments. The research organization METEOR has provided funds for conducting this experiment.

Part I

In Part I of this experiment, you control a stick figure that will walk across the screen.

Once the experiment begins, you can start walking by clicking the **"Start"** button on the left of the screen. Your stick figure will approach a series of stop lights and will stop to wait at each light. To make your stick figure walk again, click the **"Walk"** button in the middle of the screen.

The rule is to wait at each stop light until it turns green.

Your earnings in Part I are determined by the amount of time it takes your stick figure to walk across the screen. **Specifically, you begin with an initial endowment of 8 Euro**. Each second, this endowment will decrease by **0.08 Euro**.

This is the end of the instructions for Part I. If you have any questions, please raise your hand and an experimenter will answer them privately. Otherwise, please wait quietly for the experiment to begin.

H Instructions for the CPR Game

Part II

This part of the experiment will consist of several decision making periods. In each period, you will collect **60 tokens**. Your task is to decide whether to take these tokens from either or both of two accounts: a **private** account and a **group** account.

Each period you receive the sum of your earnings from your private account plus your earnings from the group account.

There are **4** people, including yourself, participating in your group. You will be matched with the same people for all of Part II. Other people in your group will make the same decisions as you.

You share the group account with other members of your group (and only with them and no one else).

Each token you take from the **private** account generates a cash return to you (and to you alone) of **one** cent (**0.01 Euro**).

Tokens taken from the **group** account yield a different return. For each token you take from the group account, you will receive a cash return of **two** cents (**0.02 Euro**).

The private account has an unlimited number of tokens that you can take, so it will never run out of tokens. However, the group account initially contains a total of **360** tokens. This is the **capacity** of the group account.

Whenever any person in your group takes tokens from the group account, the number of tokens is reduced. However, each period, some of the tokens taken from the group account will **replenish**. Specifically, they will replenish according to the following rule:

If there are **X** tokens remaining in the group account at the end of a period, the group account will replenish **(360 - X)/4** tokens. Thus, at the beginning of the next period, there will be **X + (360 - X)/4** tokens in the group account.

BUT if the total number of tokens in the group account ever falls to **fewer than 30** tokens, the group account will **not replenish**.

Finally, if at any point, the group attempts to take more tokens from the group account than actually remain in the account, the remaining tokens will be divided across the people who chose to take from the group account, and the group account will **not replenish**.

Here are three examples to make this clear:

(1) Suppose that at the beginning of the period, there are **360** tokens in the group account. Then, suppose the people in your group, including yourself, take a total of **200** tokens from the group account. At the end of the period, there would be **360 - 200 = 160** tokens remaining in the group account.

The group account would then replenish before the next period. Specifically, **(360 - 160)/4 = 50** tokens would be added back to the group account.

So, at the beginning of the next period, there would be **160 + 50 = 210** tokens in the group account.

(2) Now, suppose the next period begins with **210** tokens in the group account, and suppose that the people in your group take **200** tokens from the group account. At the end of the period, there would be **(210 - 200) = 10** tokens in the group account.

However, since **10** $<$ **30** the group account **would not replenish**, and there would only be 10 tokens in the group account at the beginning of the next period.

(3) Now, suppose the next period begins with **10** tokens in the group account. Then suppose that one person in the group attempts to collect **10** tokens from the group account, one person attempts to collect **2** tokens, and the other two people only collect from the private account.

Since there are only **10** tokens to collect, the two people who attempted to take from the group account would split the tokens according to the following rule. The first person would collect **1** token, and the second person would collect **1** token. Then the first person would collect another token, and so would the second person. Now the second person has collected all the tokens he/she chose to collect, so the first person would collect the remaining **6** tokens. In this case, the first person would get a total of **8** tokens from the group account, and the second person would get **2** tokens. They would then collect the rest of their tokens from the private account.

Each period proceeds as follows:

First, decide on the number of tokens to take from the private and the group accounts by entering numbers into the boxes labeled private and group. Your entries must sum to **60**.

While you make your decision, the **3** other members in your group will also decide on how many tokens to take from the private and group accounts.

Second, after everyone has made a decision, your earnings for that decision period are the sum of your earnings from the private and group accounts.

As an example, suppose that you take a total of **30** tokens from the private account and **30** tokens from the group account. Your total earnings from that period would be **30 + 30*2 = 90** cents. Remember, the return from the group account is **0.02 Euro** per token and the return from the private account is **0.01 Euro** per token.

While you are deciding how to allocate your tokens, everyone else in your group will be doing so as well. When the period is over the computer will display your earnings for that period and your total earnings up to and including that period.

This is the end of the instructions. If you have any questions please raise your hand and an experimenter will come by to answer them.