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Abstract

Experimental studies of common pool resource (CPR) dilemmas are frequently terminated with collapse of the resource; however, there is considerable evidence in real-world settings that challenge this finding. To reconcile this difference, we propose a two-stage model that links appropriation of the CPR and provision of public goods in an attempt to explain the emergence of cooperation in the management of CPRs under environmental uncertainty. Benchmark predictions are derived from the model, and subsequently tested experimentally under different marginal cost-benefit structures concerning the voluntary contribution to the provision of the good. Our results suggest that the severity of the appropriation problem is significantly mitigated by the presence of an option for voluntarily contributing a fraction of the income surplus from the appropriation phase to the provision of the public good.

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1. Introduction

Social dilemmas are characterized as interactive decision-making situations in which individual rationality results in Pareto-deficient outcomes. Arguably, one of the most pressing societal problems resulting from such dilemmas is the depletion of natural resources, which are, in many cases, managed under common property regimes (Ciriacy-Wantrup and Bishop 1975). Under these circumstances, a well-defined group of agents share the use of a common and divisible natural resource, generating a dilemma that results in resource depletion (Larson and Bromley 1990; Ostrom et al. 1994). The dilemma that each group member faces is between increasing their own payoff by appropriating as large a share of the common pool resource (CPR) as possible, and the need to cooperate with other group members in order to achieve Pareto-optimal outcomes and thereby prevent the depletion of the resource.

This "commons" dilemma has been the topic of extensive theoretical, empirical, and experimental research (see Ostrom et al. 1994 for an overview). While much of this research has assumed that the size and productivity characteristics of the CPR are well known by all group members, the role played by the environmental uncertainties characterizing most real-world commons, potentially complicating the attainment of Pareto-optimal outcomes in field settings (Ostrom et al. 1994), is acknowledged (Suleiman and Rapoport 1988). Results from this research generally find resource requests conforming to theoretical predictions, including circumstances in which aggregate requests might lead to complete resource collapse (Rapoport and Suleiman 1992). However, mismanagement of CPRs is by no means a universal conclusion. There is empirical evidence from many local communities that users of CPRs have succeeded over generations in devising their own rules to restrict or regulate individual requests in ways that avoid such undesirable collective outcomes (Ostrom et al. 1994). These observations have prompted a program of experimental research aimed to identify the mechanisms and variables that might explain the emergence of cooperative behavior in the commons, ranging from contextual factors such as non-binding communication (Ostrom et al. 1994), repeated interaction (Herr et al. 1997), sanctioning and reward systems (Ostrom et al. 1992), endogenous collective choice (Walker et al. 2000), and informational structures (Villena and Zecchetto 2011) to individual preferences with social value orientations, such as altruism or warm glow (Andreoni 1995).

A common assumption underlying these studies is that the problems that agents face in managing CPRs are strictly concerned with appropriation. While this assumption is made to gain analytical tractability (Ostrom et al. 1994), it detracts attention from other forms of social and economic interdependencies present in natural settings. As emphasized by Gardner et al. (1990), appropriators of CPRs often engage in a number of activities other than harvesting that ties them together. For example, farmers who jointly use an irrigation system organize a number of provision activities such as in-kind maintenance of the system (e.g., repairing irrigation ditches) or construction of structures to trap or retain agricultural waste (Dinar and Jammalamadaka 2013). A number of other examples in which appropriation and provision activities are linked together can be found in field studies examining the local governance of rice farming and fishing communities (Berkes 1986; Werthmann et al. 2010), groundwater users (Blomquist 1992), and grazing in forest-dependent communities (Agrawal 1992).

Perceiving these provision activities as supply-side provision problems (Gardner et al. 1990), the behavioral incentives that appropriators have to contribute towards provision activities parallel those of provision of pure public goods. Depending on the specific characteristics of the situation, the marginal benefit that group members derive from the public good may, or may not, exceed the marginal cost of their contribution. The former case corresponds to the notion of fully "privileged" groups (Olson 1965), in which full contribution to the public good is a dominant strategy for each group member, generating the presumption that the collective good will be provided at socially efficient levels. When the marginal value of the public good does not exceed the cost of contributing, but does not fall short of it, the group is termed "intermediate." Olson (1965) notes that the public good in this case may (or may not) be provided by the group members. Cases in which groups are neither privileged nor intermediate are classified by Olson (1965) as "latent," and a presumption exists that the collective good will not be provided, since no member of the group has an incentive to contribute to its provision. Irrespective of the particular situation, and of considerable importance to our study, the case studies mentioned above show that an additional complexity in governing CPRs is that the use of one service or resource can affect the level of provision of other services or resources and, in turn, the severity of the appropriation problem may be reduced by the subsequent presence of these provision activities.

Although accounting for these appropriation and provision interdependencies adds a layer of complexity to the analysis of the well-understood difficulties that attend the commons, we posit that it is the very presence of such interdependencies that might explain, in part, the emergence of cooperative behavior in the management of CPRs. Two factors support this argument. First, in contrast to the assumption of game independence in standard game theory, recent experimental evidence suggests that "behavioral spillovers" do exist when appropriation-like games and public goods provision games are played in ensemble, with participation in the latter affecting behavior in the former (Savikhin and Sheremeta 2012). Second, the presence of provision decisions may confer on the CPR users a "unified purpose" which has been previously proposed by Solstad and Brekke (2011) as an explanation for cooperative behavior in the commons. Based on the neutrality theorem in the literature on private provision of public goods, Solstad and Brekke (2011) show that if all group members contribute to the public good, any deviations from cooperative resource appropriation levels will be neutral in the sense that individuals offset such deviations through their own contributions to the public good. In such settings, the emergence of cooperation in the management of the common property is not accounted for by factors such as social norms, altruistic preferences, warm-glow, or infinite/indefinite interactions, but rather by the shared interest in the provision of the public good using the income surplus from the appropriation of the shared resource.

Following this line of reasoning, this paper seeks to develop a theory of cooperative behavior in the commons that addresses the link between appropriation and provision activities occurring sequentially in natural settings. In exploring this link, the model developed herein and the experiments designed to test it attempt to account for and predict when appropriators of CPRs, rationally acting upon their own self-interest, generate appropriation levels that comply with the cooperative solution. In order to increase the realism of the model, resource use decisions in the CPR are modeled under conditions of environmental uncertainty, a feature that provides a more challenging test for the emergence of cooperative behavior in the commons.

In the remainder of the paper, we first propose in Section 2 a two-stage model linking appropriation and provision decisions, and then solve it for theoretical benchmarks. Subsequently, in Section 3 we present three experimental conditions (treatments) designed to investigate appropriation behavior when provision activities are characterized by different marginal benefit-cost structures. Experimental results are presented in Section 4, and Section 5 concludes.

II. A two-stage CPR model under environmental uncertainty

We model the overall appropriation decision process of a CPR under conditions of environmental uncertainty as a two-stage game, in which stage 1 has the structure of the resource dilemma under environmental uncertainty proposed by Suleiman and Rapoport (1988), and stage 2 has the structure of the standard linear public goods game as explored, for example, by Isaac and Walker (1988).

In stage 1, a group of n agents decide simultaneously and anonymously how much to request (appropriate) from a CPR whose accurate size is unknown. Rather, it is commonly known that the resource size, denoted by X, is uniformly distributed on the $[\alpha, \beta]$ closed interval. Each of the n individuals may request any amount between 0 and β from the shared resource. After all the n requests are made, the accurate size of the resource is publicly revealed, corresponding to the random realization x of X. If the sum of group requests is less than or equal to x, then each agent is awarded his/her request. On the other hand, if the sum of group requests exceeds the size x of the resource, it collapses and each individual's payoff is zero. In the latter case, the game ends. In the former case, it proceeds to stage 2.

In stage 2, the same group of n agents has the opportunity to simultaneously and voluntarily contribute to a public good using the earnings from stage 1. Once all group members have submitted their contributions, the aggregate contribution to the public good is announced and individual earnings are calculated. This stage is implemented as a public goods game with a linear payoff schedule. If an individual contributes c dollars to the public good, then each group member (including the contributor) receives mc dollars from that contribution. Thus, the returns from contributions to the public good are both non-excludable and non-rivaled. Moreover, the amount not contributed to the public good may be thought as money allocated to the consumption of private goods.

Assuming linear utility functions, and letting r_j denote the request made by individual j in stage 1 and c_j his/her contribution in stage 2, the expected payoff to the individual from the two-stage game is given by:

$$\pi_j = \begin{cases} r_j - c_j + m\sum_{j=1}^{n} c_j & if \quad \sum_{j=1}^{n} r_j \leq \alpha \\ \left(r_j - c_j + m\sum_{j=1}^{n} c_j\right) \times Prob\left(\sum_{j=1}^{n} r_j \leq x\right) & if\ \alpha < \sum_{j=1}^{n} r_j \leq \beta \\ 0 & if \quad \sum_{j=1}^{n} r_j > \beta \end{cases} \quad (1)$$

The Nash equilibrium solution of this game is derived by backward induction. Thus, the second-stage Nash equilibrium is computed for each possible outcome of the first-stage game. The payoff to player j in the second-stage is $\pi_j = r_j - c_j + m\sum_{j=1}^{n} c_j$. The individual optimality condition requires an evaluation of the marginal effects of contributing to the public good and keeping the amount of first-stage requests. These conditions can be compared by taking the derivative of the payoff function in the second stage with respect to the individual contributions c_j. This derivative is $-1+m$. Thus, m is the marginal per capita return (MPCR) of a contribution to the public good, and the marginal return of keeping the amount of first-stage requests is 1.

As long as $m<1$, the dominant strategy for each individual is to contribute nothing to the provision of the public good. Contributions to the public good increase aggregate payoffs, compared with keeping the first-stage requests for private consumption if $n \times m>1$ (notice that $m \leq 1/n$ implies that group payoffs are *not* maximized when all individuals contribute to the public good). Thus, if $1/n<m<1$, the game poses a social dilemma in contributions, since total payoffs are maximized by each individual contributing the full amount *rj* to the public good, while the Nash equilibrium entails that each individual keeps the whole amount for private consumption. If $m>1$, then the unique equilibrium entails that each individual contributes the full amount to the public good, which coincides with the maximization of group payoffs. Finally, if $m=1$, then there is a continuum of equilibria with each individual contributing any amount of stage 1 requests to the public good.

We may now derive the symmetric Nash equilibrium solution for the resource dilemma game. To do so, we first differentiate the quadratic component in Equation (1) with respect to r_j and equate the result to zero. Letting $c_j=\gamma_j r_j$, where $0 \leq \gamma_j \leq 1$ is the fraction of first-stage request contributed to the public good, and noting that $Prob\left(\sum_{j=1}^{n} r_j \leq x\right) = (\beta - \sum_{j=1}^{n} r_j)/(\beta - \alpha)$, the result is:

$$\frac{\left(\beta - 2r_j^* - \sum_{i \neq j} r_i^*\right)^2 \left(1 + (m-1)\gamma_j\right) - m \sum_{i \neq j} \gamma_i r_i^*}{\beta - \alpha} = 0. \qquad (2)$$

It can easily be seen that the second derivative is negative, as required for a maximum. Assuming symmetry, so that $r_j^* = r_i^*$, the first-stage equilibrium request is given by:

$$r_j^* = \frac{\beta + (m-1)\gamma_j \beta}{2 + 2(m-1)\gamma_j + (n-1)(1 + (m-1)\gamma_j) + m \sum_{i \neq j} \gamma_i}. \qquad (3)$$

To characterize the subgame-perfect equilibrium for the two-stage game, we need to combine the second-stage solutions with equation (3). This requires an analysis of three possible cases: (a) the case where $1/n<m<1$; (b) the case where $m>1$; and, (c) the case where $m=1$. These three cases correspond to the tracheotomy of latent, fully privileged, and intermediate groups introduced by Olson (1965). We turn next to these analyses.

A. The case of "latent" groups: 1/n<m<1

For $m<1$ in stage 2, no one contributes to the public good in equilibrium, i.e., $\gamma_j = \gamma_i = 0$. Thus, $r_j^* = \frac{\beta}{(n+1)}$. However, it is important to note that this solution does not constitute the equilibrium request in all first-stage cases. If $\sum_{j=1}^{n} r_j \leq \alpha$, then any vector of requests $\mathbf{r}^*=(r_1, r_2, \ldots, r_n)$ whose elements satisfy the condition that $\sum_{j=1}^{n} r_j^* = \alpha$ is an equilibrium solution for the first-stage game. Assuming symmetry, the solution is $r_j^* = \frac{\alpha}{n}$. Therefore, the subgame-perfect Nash equilibrium for the two-stage game is:

$$r_j^* = Max\left(\frac{\alpha}{n}; \frac{\beta}{(n+1)}\right) \qquad and \qquad c_j^* = 0. \qquad (4)$$

As noted above, when $1/n<m<1$, the Pareto optimal solution of the second-stage game entails full contribution to the public good by each group member. The Pareto optimal request of stage 1 can be solved as before, but assuming that only one agent is in charge of the resource. Assuming, as before, symmetry and risk neutrality on the part of group members, it can easily be checked that the Pareto optimal solution (which is independent of m and γ in the first-stage) for the two-stage game is:

$$r_j^{**} = Max\left(\frac{\alpha}{n}; \frac{\beta}{2n}\right) \qquad and \qquad c_j^{**} = r_j^{**}. \tag{5}$$

Comparison of Equations (4) and (5) shows that the equilibrium contribution is Pareto deficient, and that the equilibrium request is also Pareto deficient if $\alpha < n(\beta - \alpha)$. Importantly, notice that the equilibrium request in the case of latent groups coincides with the equilibrium request that would be predicted if the game consisted of stage 1 only.

B. The case of fully "privileged" groups: m>1

For *m>1* in stage 2, every group member contributes to the public good in equilibrium, i.e., $\gamma_j = \gamma_i = 1$. This result can be used in Equation (3) to derive the Nash equilibrium request for the quadratic component in Equation (1). Doing so yields $r_j^* = \frac{\beta}{2n}$. As before, the solution $r_j^* = \frac{\alpha}{n}$ is also an equilibrium solution satisfying the condition that $\sum_{j=1}^{n} r_j^* = \alpha$.

Therefore, the subgame-perfect equilibrium for the two-stage game in this case is:

$$r_j^* = Max\left(\frac{\alpha}{n}; \frac{\beta}{2n}\right) \qquad and \qquad c_j^* = r_j^*. \tag{6}$$

It can easily be seen in this case that both the equilibrium contribution and the equilibrium request are Pareto efficient.

C. The case of "intermediate" groups: m=1

For *m=1* in stage 2, individual group members are indifferent between contributing any amount to the public good or not contributing. Substituting the value of *m* into Equation (3) allows us to derive the subgame-perfect Nash equilibrium for the two-stage game as:

$$r_j^* = Max\left(\frac{\alpha}{n}; \frac{\beta}{(n+1)+\sum_{i\neq j}\gamma_i}\right) \qquad and \qquad c_j^* \in [0;\ r_j^*]. \tag{7}$$

Notice that assuming an interior solution where all other group members contribute to the public good, the Nash equilibrium request by individual *j* coincides with the Pareto optimal request, irrespective of her own contribution. In this case, the solution to the resource dilemma is socially efficient, even if contributions to the public good turn out to be socially inefficient due to free riding by player *j*. On the other hand, assuming an interior solution where none of the other group members contribute to the public good, the Nash equilibrium request by individual *j* is Pareto deficient if $\alpha < n(\beta - \alpha)$, irrespective of her own contribution to the public good.

III. Experimental design and theoretical predictions

A. Procedures, parameters and treatments

We designed a simple experiment operationalizing the two-stage game under environmental uncertainty described by equation (1), with groups composed of five (*n*=5) subjects and a commonly known resource size that is uniformly distributed on the [250, 750] closed interval, for an uncertainty range of 500 and an expected value of 500. Each subject participated in 40 repetitions (rounds) of the same two-stage game. Prior to the first game, each subject was randomly and anonymously assigned to a fixed group for the duration of the session. We implemented three MPCR conditions in a between-subject design. In the first condition, the parameter *m* was set equal to 0.5 (hereinafter, "Treatment I"); in the second and third conditions it was set equal to 1.0 ("Treatment II") and 1.5 ("Treatment III"), respectively. These three values were chosen to capture the incentives faced by latent, intermediate, and fully privileged groups in stage 2 of the game.

At the beginning of each experimental session, subjects were provided with written instructions informing them that they could, individually and simultaneously, request from 0 up to 750 tokens from a shared resource, and that the precise value of the resource (called "random draw") in any round was to be randomly extracted (and publicly announced) after all group members made their requests. Subjects were also informed that if the sum of group requests exceeded the randomly determined resource size in the round, then their individual payoffs in that round would be zero, and the game would terminate; otherwise, their individual payoffs in the round would equal their individual requests, and the game would continue to a subsequent stage in which they could contribute any fraction of their individual payoffs to a joint group project after observing the individual requests by all group members. Subjects were also informed that, in the latter case, their final payoffs for the round would equal the amount not contributed to the group project, plus the sum of group contributions multiplied by the value of *m* (based on the implemented treatment).

In addition to a $5 participation fee, at the end of the session subjects were paid for the tokens accumulated in six (randomly determined for each subject) out of the 40 rounds, in which each token was worth 2 US cents. This procedure was implemented to prevent wealth effects. Each experimental treatment was implemented using the *z-Tree* (Fischbacher 2007) software, and each session lasted for about one hour. No communication between the subjects was allowed in any of the treatments. All the experimental sessions were conducted at the Behavioral Research Lab at the University of California, Riverside (UCR), which is a standard computerized laboratory with subjects' stations placed in separate cubicles to ensure privacy. Subjects were recruited from the pool of UCR students registered to participate in research studies through the web-based subject recruitment. A total of 90 subjects participated in this experiment, 30 (six different groups) of them in each of the three treatments.

B. Theoretical predictions

Table 1 presents theoretical predictions that are used as social welfare maximizing and equilibrium benchmarks for the analysis of the data from the three treatments. The Pareto-optimal request and contribution level, shown in the left panel of Table 1, are the same across the three treatments. In each case, the behavior that maximizes the aggregate payoff to all players entails full contribution of their income from the use of the shared resource to the public good, and a symmetric individual request (r) of 75 tokens at stage 1 of the game, for a total group request (R) of 375 tokens. The probability of receiving this request (p) is 0.75, yielding an expected payoff of Π=56.25 tokens in the first stage of the game. This corresponds to the maximum symmetric expected income from the use of the shared resource that subjects may achieve in this game, which they may then use to provide the public good.

The symmetric subgame-perfect equilibrium requests and contribution levels are presented in the right panel of Table 1. They coincide with the Pareto-optimal solutions in the case of the fully privileged groups of Treatment III, who have a dominant strategy of full contribution of their earnings from the use of the resource to the public good

(γ=1). Conversely, individuals in the latent groups of Treatment I have a dominant strategy of zero contribution to the public good (γ=0), implying a Pareto-deficient symmetric individual request of 125 tokens in equilibrium, for a total group request of 625 tokens. The corresponding probability of receiving this request (p) is 0.25, yielding an expected payoff of Π=31.25 tokens in stage 1 of the game. Comparing the expected payoffs from following the subgame-perfect equilibrium strategy to the Pareto-optimal solution yields an efficiency index (E) of 56%. This means that subjects are expected to achieve 56% of the maximum expected payoffs that may be achieved from the use of the resource if they follow the subgame-perfect equilibrium strategy in this treatment.

Whereas the contribution stage in Treatments I and III has a unique dominant strategy of zero and full contribution, respectively, it has a continuum of Pareto-ranked Nash equilibria in Treatment II. This feature of the game also gives rise to a continuum of Pareto-ranked equilibria at the request stage, one of which is perfectly efficient. The Pareto-optimal equilibrium of the two-stage game in Treatment II is marked in italics in Table 1, where γ=1. The least efficient equilibrium (hereinafter referred to as "Suboptimal NE") of Treatment II is also marked in italics, where γ=0. Whether individuals in these intermediate groups adopt Pareto-optimal or suboptimal strategies is theoretically undetermined. This stands in stark contrast with the unique equilibrium predictions in Treatments I and III.

While the multiplicity of equilibria increases strategic uncertainty and, as a consequence, the probability of coordination failure (Van Huyck et al. 1990), it also underscores an important theoretical feature of Treatment II. Because there is no dominant contribution strategy, individuals in Treatment II may strategically use their requests from the shared resource as a means to influence the behavior of other players at the contribution stage. Thus, a significant restraint in individual requests by the group members, which can be considered cooperative behavior in managing the commons, may be the result of such individually rational *strategic* attempts to elicit provision of the public good at stage 2 of the game. Although the same type of strategic play may behaviorally be appealing to the subjects in Treatments I and III, they do not make part of a subgame-perfect equilibrium strategy in these treatments, since no contribution and full contribution to the public good are, respectively, players' best responses in Treatments I and III, irrespective of requests at the first-stage of the game.

Finally, the equilibrium predictions in Table 1 are predicated on the assumption that individuals are sophisticated in the sense that they exercise foresight and consider the second-stage incentives when devising an equilibrium strategy for stage 1 of the game. In practice, however, such a strategic reasoning process may be problematic, and agents may instead adopt myopic strategies, viewing the request decision as only one stage in a sequence of games. In that case, the symmetric individual request in each of the treatments would equal 125 tokens, for a total group request of 625 tokens. Notice that, as pointed out in the previous section, such myopic requests coincide with the unique subgame-perfect requests of Treatment I and with the least efficient subgame-perfect requests of Treatment II. Observation of such request outcomes in these two treatments may be a consequence of myopic or strategic decision behavior. However, this is not so in Treatment III, in which the values of myopic requests do not make part of subgame-perfect predictions, thereby allowing for a clear distinction between the play of myopic or strategic strategies. [1]

IV. Experimental results

The analysis of behavior within our experimental design is organized by examining in order: (A) resource-use behavior in stage 1 of the game in each treatment, (B) contribution decisions to the public good in stage 2 of the game, and (C) the relationship between resource-use and contribution decisions in each treatment. In each case, the main findings are presented in the form of summary results. [2]

A. First-stage results

If subjects behave myopically, believing that the presence of provision activities has no impact on resource-use decisions, we should observe no differences in requests across treatments. In contrast to this prediction, we can report the following result.

Result 1. O*utcomes of myopic play are poor predictors of behavior, with resource-use behavior by all types of groups revealing a high degree of foresight in the two-stage setting.*

Support for Result 1 is presented in Table 2. Columns 2 and 3 of Table 2 report, respectively, the mean individual requests over all 40 rounds in each treatment, and the first-stage efficiency index implied by such requests.[3] The frequency at which requests were awarded, continuing the game to the second stage is presented in column 4 (the observed frequency of resource destruction in each treatment being the complement to this figure). The table reveals that, pooling across all rounds, mean individual requests are about 101, 81, and 90 tokens in Treatments I, II, and III, respectively. These requests are, therefore, lowest in Treatment II and highest in Treatment I. A pairwise application of the Kolmogorov-Smirnov test for the equality of distribution functions shows that these differences in requests are significant at all conventional significance levels ($p<0.0001$). Clearly, mean requests in all treatments are substantially lower than the 125 predicted value had subjects ignored the second-stage incentives when making their request decisions. These results stand in stark contrast with the findings from previous experimental implementations of the CPR game as a single-stage game. For example, using the same parameters, Rapoport and Suleiman (1992) reported a mean individual request of 132.3 tokens in the single-stage game with groups of five players simultaneously requesting from a CPR whose size was uniformly distributed on the [250-750] interval. Other experimental results supporting the suboptimal equilibrium predictions of the single-stage CPR game under conditions of environmental uncertainty were reported by Rapoport et al. (1992). Thus, evidence from the three treatments rejects the hypothesis of myopic behavior in the two-stage decision making process.

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[1] See Talluri and Van Ryzin (2004) for a discussion of the consequences of myopic and strategic decisions in revenue management.

[2] Although the analysis in the text focuses on individual behavior, all the results presented are supported by an extensive analysis (available from the authors) of behavior conducted at the group level.

[3] The ratio of observed payoffs to maximal predicted payoffs at optimal benchmarks is often used in experiments as a measure of performance/efficiency to compare the effects of various treatments. Because the first-stage payoffs in our treatments depend not only on subjects' requests but also on the random draw in the experimental sessions, a better measure of efficiency ensuring comparability across the treatments takes the expected payoff in the first stage of the game, rather than the actual payoff, as the numerator in the efficiency ratio. Thus, the efficiency index is measured by the ratio of expected payoff at the given request to the expected payoff at the Pareto-optimal request.

These observations are corroborated by examining the evolution of request behavior over time. Remember that a general finding in repeated CPR games is that behavior is consistent with efficient outcomes in the first few rounds of play, and approaches the equilibrium prediction of resource-overuse in the last rounds. Our next result provides information as to whether the presence of provision activities prevents the convergence to the single-shot equilibrium request level by the subjects in the latent groups of Treatment I.

Result 2. *Mean requests by subjects in latent groups are in between the Nash equilibrium prediction and the Pareto-optimal solution, converging to an equal-sharing of the expected value of the resource. Efficiency is high and resource destruction is low, compared with equilibrium predictions.*

Support for Result 2 comes from Figure 1, the summary statistics in Table 2, and from formal statistical analyses accounting for the presence of time and repeated interaction effects reported in the top panel of Table 3. Figure 1 depicts the evolution of the mean requests over time in each treatment. It is clear from the figure that mean requests in Treatment I tend to lie everywhere below the equilibrium prediction of 125 tokens, with no steady pattern of convergence towards this prediction. These impressions are confirmed by the estimation of the Ashenfelter-El Gama model described in Noussair et al. (1995). For each treatment, this model is specified as:

$$y_{it} = \beta_{11}G_1(1/t) + \beta_{12}G_2(1/t) + \beta_{13}G_3(1/t) + \beta_{14}G_4(1/t) + \beta_{15}G_5(1/t) + \beta_{16}G_6(1/t) + \beta_2(t-1)/t + u_{it}$$

where y_{it} is the request made by subject *i* at time *t*, G_i is a dummy variable taking the unit value for all subjects in group *i* and 0 otherwise, *t* represents time as measured by the number of rounds in the experiment, *u* is the error term, and the β's are parameters to be estimated. In this specification, the weight of β_2 is zero when *t*=1, and only the values of β_{1i} determine the dependent variable. As *t* gets large, however, the weight of β_2 gets large because $(t-1)/t$ approaches unity, while the weight of β_{1i} gets small because $1/t$ approaches zero. Thus, the parameters β_{1i} measure the origin of a possible convergence process for each group, and the parameter β_2 measures the asymptote of the convergence process of the dependent variable. Therefore, the latter is the main focus of the model since it represents the long-term tendency of the magnitude of the dependent variable. Because we are modeling a dynamic process, we allow for heteroskedasticity across subjects within the treatments, and also allow for the presence of first-order individual-specific autocorrelation in our estimation procedure.

The estimated results of this model reported in Table 3 show that individual requests in Treatment I (r_I) converge to a value of about 96 tokens, with individual requests in half of the groups converging toward this common asymptote from above, and half of them converging from below, reflecting the heterogeneous adjustment and repeated interaction effects across the groups.[4] Although the asymptotic point estimate of requests is a bit lower than the overall mean, a long-term tendency to an equal sharing of the expected value of the resource (i.e., a request of 100 tokens) is not rejected as indicated by the 95% confidence limits of this estimate. As shown in the third column of Table 2, these requests imply a mean efficiency index of 80%, significantly higher than

[4] In addition to the estimates of the model given in the text, an alternative specification was estimated allowing the time series to converge to a different value for each group within each treatment. These estimates are not given here because they do not alter the main conclusions in the text.

the 56% predicted efficiency at the equilibrium request. Accordingly, although the 44% frequency of resource destruction in Treatment I exceeds the 25% Pareto-optimal prediction by 19 percentage points ((100-56)-25), it is also substantially lower than the 75% equilibrium prediction, falling 31 percentage points below it.

Turning to the analysis of the evolution of request behavior over time in Treatment II, we can report the following result.

Result 3. *Mean requests by subjects in intermediate groups approximate the Pareto-optimal prediction. As a result, efficiency is considerably high, and resource damage is avoided at socially efficient levels.*

The dynamics of the subjects' requests in Treatment II depicted in Figure 1 reveal the generally documented tendency for mean requests to increase over time. On average, requests are below the Pareto-optimal prediction of 75 tokens for the majority of the first 20 rounds, increasing steadily towards the second part of the experiment. The results of the estimation of the Ashenfelter-El Gama model in Table 3 show that individual requests in Treatment II (r_{II}) converge to 81 tokens, with only one group exhibiting a pattern of convergence from below at very low request levels. This estimate does not differ from the overall mean request by the subjects in Treatment II, which exceeds the Pareto-optimal prediction by just six tokens (8%). These requests imply an efficiency index of 93%, a figure that is considerably high and clearly far apart from the 56% predicted efficiency at the suboptimal equilibrium request. Arguably, more than harvesting levels or efficiency considerations, the most important measure of welfare from a societal point of view is the probability of resource collapse associated with the management of CPRs. As shown in Table 2, the observed frequency of resource destruction by the groups in Treatment II is 28%. This figure compares favorably with that implied by Pareto-optimal requests, and the difference is not statistically different from zero at conventional significance levels (z=1.192, p=0.233). Thus, although their requests are slightly above the point prediction for the socially efficient outcome, subjects in Treatment II are successful in avoiding the resource damage at socially efficient levels.

Next, we turn to the evolution of request behavior over time in Treatment III, reporting the following result.

Result 4. *Mean requests by subjects in fully privileged groups exceed the Pareto-optimal prediction. As a result, efficiency is lower, and resource destruction higher, than the equilibrium predictions.*

The support for Result 4 can be seen in Figure 1, Table 2, and the estimates in Table 3. Figure 1 reveals that mean requests in Treatment III are in between mean requests in Treatments I and II in the first 20 rounds of play, tending to approximate the latter in the last 20 rounds. The long-term tendency of requests by the subjects in fully privileged groups (r_{III}) is estimated at 87 tokens, as shown by the results in Table 3. This estimate is lower than the overall mean request of 90 tokens, but it is not statistically different from it as indicated by the width of its 95% confidence interval. Moreover, comparison of the 95% confidence limits of the asymptotic request value across the treatments reveals that they do not overlap, indicating that the differences in requests' convergence across treatments are statistically significant at better than the 5% significance level, with those in Treatment III significantly higher (lower) than those observed in Treatment II (I). Accordingly, the implied efficiency index in Treatment III is in between that in the other two treatments, at a value of 87%. As shown in Table 2, the frequency of resource destruction is 35% in Treatment III, significantly exceeding the Pareto-optimal prediction by 10 percentage points.

B. Second-stage results

As noted previously, subjects in the different treatments differed in their ability to avoid destruction of the common resource in stage 1 of the game. Consequently, the number of rounds in which contribution decisions are made (called "contribution rounds") by the subjects is not the same across treatments. The maximum number of observed contribution rounds is 29, 34, and 33 by the subjects in Treatments I, II and III, respectively.

Figure 2 depicts the mean contributions to the public good as a fraction of subjects' endowments (i.e., income from the use of the shared resource) over contribution rounds in each treatment. Several useful observations can be drawn from the figure. First, no strong tendency for contribution fractions to drop over time to very low levels is observed in either treatment. This finding is consistent with results of Saijo and Nakamura (1995), who also reported fairly stable contribution rates in experimental treatments varying the MPCR (m=0.7 vs. m=1.4) to the public good. Secondly, and conforming to a priori expectations, contribution fractions are clearly lower in Treatment I than Treatments II and III. Specifically, concerning contribution behavior in the observed contribution rounds by members of the latent groups of Treatment I, we report the following result.

Result 5. *Mean contribution rates by subjects in latent groups coincide with the 40%-60% contribution rate previously found in linear public goods games in which the unique equilibrium solution entails each player making a zero contribution.*

In addition to the results exhibited in Figure 2, support for Result 5 comes from the summary statistics presented in the right-hand column of Table 2, along with the results of the formal statistical analysis reported in the bottom panel of Table 3, with estimates obtained through a similar estimation procedure to the one previously reported, but considering contribution fractions in each treatment as the dependent variable in the Ashenfelter-El Gama model. The long-term tendency of contribution fractions by the subjects in latent groups (γ_I) is estimated at 44%, as shown by the results in Table 3. This estimate is lower than the overall mean contribution rate of 47% (Table 2), but it is not statistically different from it as indicated by the width of its 95% confidence interval.

Concerning behavior in the observed contribution rounds by the subjects in the intermediate and fully privileged groups of Treatments II and III, we report the following result.

Result 6. *Mean contribution rates by subjects in intermediate and fully privileged groups coincide with the 60%-90% contribution rate previously found in linear public goods games, in which the unique equilibrium solution entails each player making a full contribution.*

As shown in Table 2, mean contribution rates amount to 76% and 72% of subjects' endowments in Treatments II and III, respectively. These rates are significantly higher than the contribution rates observed in Treatment I, as indicated by the 95% confidence limits of the asymptotic contribution rates in each treatment shown in Table 3. The width of these confidence intervals also reveals that the difference in asymptotic contribution rates between Treatments II and III is statistically insignificant, and that they are not statistically different from their respective overall mean contribution rates. Notice that in each case contribution rates fall short of fully efficient contribution outcomes, lying in the range previously reported in linear public goods games prescribing full contribution as dominant strategies (Brandts and Schram 2008).

C. Relationship between requests and contributions

An important result from the previous analyses is that although subjects in Treatments II and III contribute similar proportions of their endowments to the public good, requests by the former are significantly lower than requests by the latter. This result suggests that more cooperative behavior in the commons is needed from subjects in intermediate groups in order to generate the same levels of public good provision as that achieved by subjects in fully privileged groups. A counterfactual statistical analysis predicting the contribution fractions by subjects in Treatment II *if* they had made the same level of requests by the subjects in Treatment III provides support for this view.

Result 7. *Subjects in intermediate groups strategically use their requests from the shared resource as a means to influence behavior at the contribution stage.*

Table 4 and Figure 3 provide support for Result 7. Table 4 contains the estimated effect of requests on contribution fractions (γ), conditional on survival of the resource, in each treatment. Given the differential nature of the material incentives embodied in the second-stage of the game, we would expect a positive (negative) relation between request and contribution behavior in Treatment III (I) as self-interested income maximizers request more in stage 1 of the game in both treatments, but contribute more (less) of their endowment in Treatment III (I). As noted previously, although self-interested income maximizers in Treatment II are indifferent between contributing or not contributing any amount of their endowment to the public good, strategic considerations may result in a negative relation between request and contribution behavior, as subjects attempt to elicit provision of the public good through more cooperative behavior in stage 1 of the game. Albeit of relatively small magnitude, the results in Table 4 conform to these expectations, with increased requests impacting negatively the contribution fractions in Treatments I and II, and positively the contribution fractions in Treatment III.

Having found a differential impact of requests on contribution behavior in Treatments II and III, we now evaluate the contribution fractions that would have been observed in Treatment II in the counterfactual scenario where requests were at the levels observed in Treatment III. This is accomplished using the coefficient vector from the model relating requests and contributions in Treatment II and the observed behavior in Treatment III to predict what fraction of their endowments subjects in Treatment II *would* have contributed to the public good *if* they had faced the level of requests observed in treatment III.[5] The cumulative frequency distribution of this counter-factual predicted contribution fraction is exhibited by the dashed line in Figure 3. Also exhibited in the figure (solid line) is the predicted contribution resulting from the estimated model using the actual requests in Treatment II. Figure 3 clearly reveals that contribution fractions by subjects in Treatment II would have been substantially lower had they faced the same level of requests observed in Treatment III. On average, subjects are predicted to contribute 76% of their endowment using the coefficient vector of the estimated model

[5] For completeness, counter-factual predictions for contribution fractions in Treatment III were generated using observed request behavior in Treatment II. The resulting mean predicted counter-factual fraction is 71% of subjects' endowments, indicating that the lower level of requests observed in Treatment II would *not* generate different contribution decisions from those observed in Treatment III, given the actual request behavior in this treatment.

for Treatment II and the actual data for this treatment, a figure that matches its overall mean contribution fraction. The counterfactual predicted contribution fraction is, on average, 69%, and the application of the Kolmogorov-Smirnov test for the equality of distribution functions shows that differences between the actual and counterfactual predicted contribution fractions are significant at all conventional significance levels ($p<0.0001$). In addition to the differential impact of requests on contribution behavior across treatments, these results show a high degree of strategic behavior with subjects in intermediate groups taking the second-stage strategic effects of their first-stage requests into consideration when stating their requests.

V. Conclusion

The present paper proposes a two-stage model linking appropriation and provision decisions for studying resource dilemmas under conditions of environmental uncertainty. An important feature of the model is that it is possible for users of common property resources to collectively achieve Pareto-optimal outcomes without the aid of central authority. Using the framework of non-cooperative game theory, we identify circumstances in which individual rational users of shared resources make appropriation decisions that are both Pareto optimal and in a non-cooperative equilibrium. This prediction occurs when groups are fully privileged in the sense that each of its members has a dominant strategy of full contribution of the income surplus from the use of the shared resource to a public good. It also occurs in the case of intermediate groups, when group members strategically exercise restraint in personal harvest as a means to foster cooperation in the provision of the public good, thereby maximizing their total income. We further identify circumstances in which the presence of provision activities does not elicit cooperative behavior in the commons. This prediction occurs in the case of latent groups, in which free-riding on the provision efforts of others is a dominant strategy for each group member, as well as in the case of intermediate groups in which members do not care about the public good. In both of these cases, equilibrium appropriation levels from the shared resource are Pareto-deficient, and coincident with those predicted for the resource dilemma in the absence of provision activities.

In a between-subject experimental design operationalizing the theoretical model, we examine behavior by fully privileged, intermediate, and latent groups of the same size and facing the same level of environmental uncertainty with respect to the size of the resource stock. Considered jointly, the results of these experiments generate four principal findings. First, the mere presence of subsequent provision decisions that depend upon the income generated from the use of the shared resource suffices to elicit individual restraint in harvesting behavior, even in the case of latent groups. In fact, latent groups are seen to make requests falling in between equilibrium and Pareto-optimal predictions, conserving the resource at high-efficiency levels, and exceeding equilibrium contributions to the public good by substantial amounts. These results for latent groups stand in sharp contrast with the high requests and resource-destruction levels found in previous studies implementing the resource dilemma as a single-stage game using the same environmental uncertainty parameters. Second, resource requests by intermediate and privileged group members are significantly lower, and contributions to the public good significantly higher, than those made by latent groups. In particular, intermediate groups are seen to avoid resource damage at socially efficient levels. Third, although contributions to the public good do not differ between intermediate and privileged groups, approaching efficient levels in both cases, resource-use behavior is generally more efficient in the former than in the latter groups. This result suggests that more cooperative behavior in the commons is needed from intermediate groups in order to generate the same levels of public good provision as that achieved by fully privileged groups. Fourth, myopic outcomes are poor predictors of behavior. relative to the sophisticated solution concepts, with resource-use behavior by all types of groups revealing a high degree of foresight in the two-stage setting.

Overall, these results contribute to the reconciliation between the overharvesting of common property resources, typically observed in experimental settings without contextual or institutional constraints on behavior and the efficient or almost efficient management of these resources as exercised by many local communities in natural-occurring settings. Furthermore, they show that it is possible to view users of common property resources as individually rational, self-interested income maximizers, and, at the same time, collectively achieving highly efficient outcomes or even preventing resource damage at fully efficient levels as demonstrated by the intermediate groups in our experiment.

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Table 1 – Pareto optimal and equilibrium benchmarks (n=5, α=250, β=750)

Treatment	Pareto optimal strategies					Symmetric equilibrium strategies					
	R	r	p	Π	γ	R	r	p	Π	γ	E
I : m=0.5	375	75	0.75	56.25	1	625	125	0.25	31.25	0	56%
II : m=1.0	375	75	0.75	56.25	1	*625*	*125*	*0.25*	*31.25*	*0*	*56%*
						375	*75*	*0.75*	*56.25*	*1*	*100%*
III: m=1.5	375	75	0.75	56.25	1	375	75	0.75	56.25	1	100%

Note: R is total group request; *r* is individual (symmetric) request; *p* is the probability of receiving the request and continuing the game to the second-stage; *Π* is the individual expected payoff in the first stage of the game; *γ* is the fraction of first-stage payoff contributed to the public good; *E* is the efficiency index of first-stage expected payoffs from adoption of equilibrium strategies.

Table 2 – Means (standard deviations) of individual requests and contributions

Treatment	r	E	p	γ
I : m=0.5	100.90 (59.18)	0.80 (0.43)	56%	0.47 (0.34)
II : m=1.0	81.32 (38.45)	0.93 (0.37)	72%	0.76 (0.31)
III: m=1.5	90.24 (70.07)	0.87 (0.55)	65%	0.72 (0.30)

Note: r is individual request; *E* is the implied efficiency index of first-stage payoffs; *p* is the percentage of rounds continuing the game to the second-stage; *γ* is the fraction of first-stage individual payoff contributed to the public good.

Table 3 – Convergence over time of individual requests and contribution fractions

Dependent Variable	Coefficient Estimates (Standard Error)							95% CI for β_2	
	β_{11}	β_{12}	β_{13}	β_{14}	β_{15}	β_{16}	β_2	LL	UL
Requests:									
r_I	122.81	70.15	207.70	145.09	72.58	65.55	96.11	91.93	100.29
	(11.55)	(11.64)	(17.89)	(17.21)	(13.42)	(16.84)	(2.13)		
r_{II}	38.55	121.23	86.29	112.55	91.88	92.19	81.13	78.69	83.58
	(8.23)	(11.59)	(7.99)	(9.37)	(8.48)	(6.12)	(1.25)		
r_{III}	84.89	86.03	81.75	166.56	146.30	53.23	87.16	83.95	90.36
	(12.32)	(4.72)	(7.21)	(22.47)	(12.76)	(15.13)	(1.63)		
Fractions:									
γ_I	0.39	0.39	0.41	0.59	0.40	0.57	0.44	0.34	0.53
	(0.10)	(0.10)	(0.11)	(0.11)	(0.11)	(0.11)	(0.05)		
γ_{II}	0.66	0.48	0.80	0.49	0.55	0.50	0.79	0.70	0.88
	(0.09)	(0.09)	(0.09)	(0.10)	(0.09)	(0.09)	(0.05)		
γ_{III}	0.56	0.72	0.34	0.47	0.50	0.68	0.76	0.67	0.84
	(0.09)	(0.09)	(0.09)	(0.09)	(0.09)	(0.09)	(0.04)		

Note: LL and UL are, respectively, the lower and upper limit of the 95% confidence interval (CI) for the asymptotic value of the dependent variable as measured by the parameter β_2.

Table 4 – Marginal effects of requests on contribution fractions

Dependent Variable	Estimate	Std. Error	*z*-statistic	*p*-value
γ_I	-0.0008	0.0003	-2.48	0.013
γ_{II}	-0.0006	0.0003	-1.69	0.092
γ_{III}	0.0006	0.0002	2.64	0.008

Note: Given that the dependent variable is naturally bounded between 0 and 1, the estimation of the model's coefficients uses the specification developed by Papke and Wooldridge (1996). To control for time and repeated interaction effects, the model also contains period dummies and the cumulative count of failed request awards up to a given period in the experiment.

Figure 1 – Mean individual requests by treatment

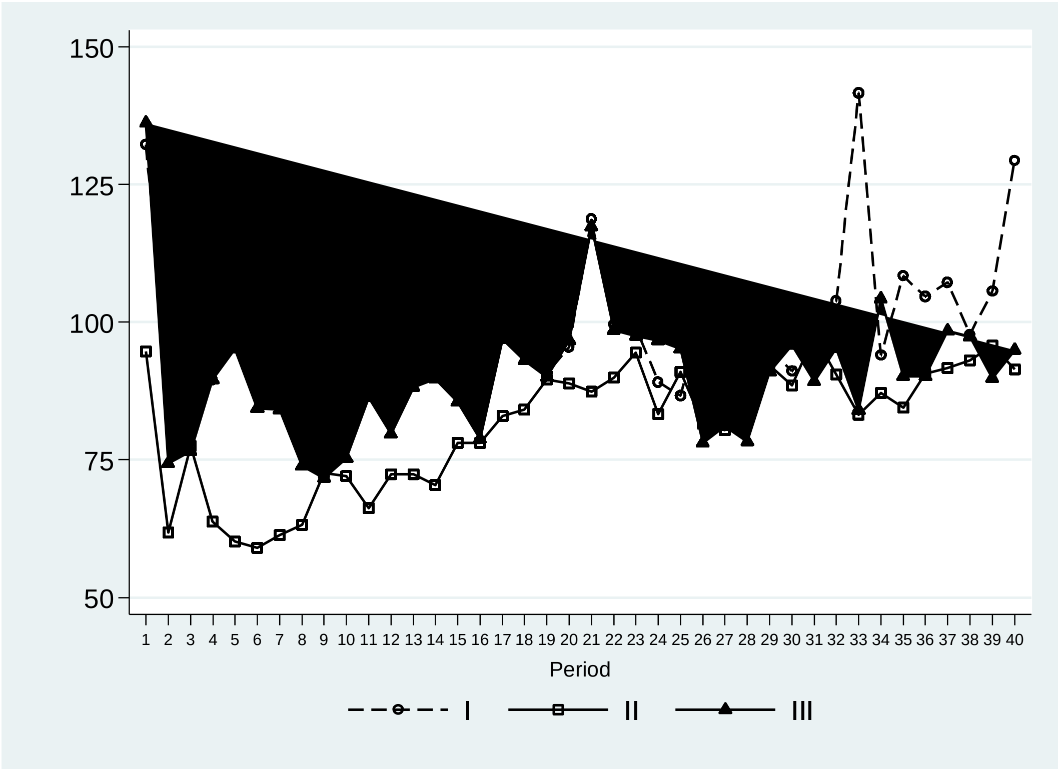

Figure 2 –Contribution as a function of subjects' endowments by treatment

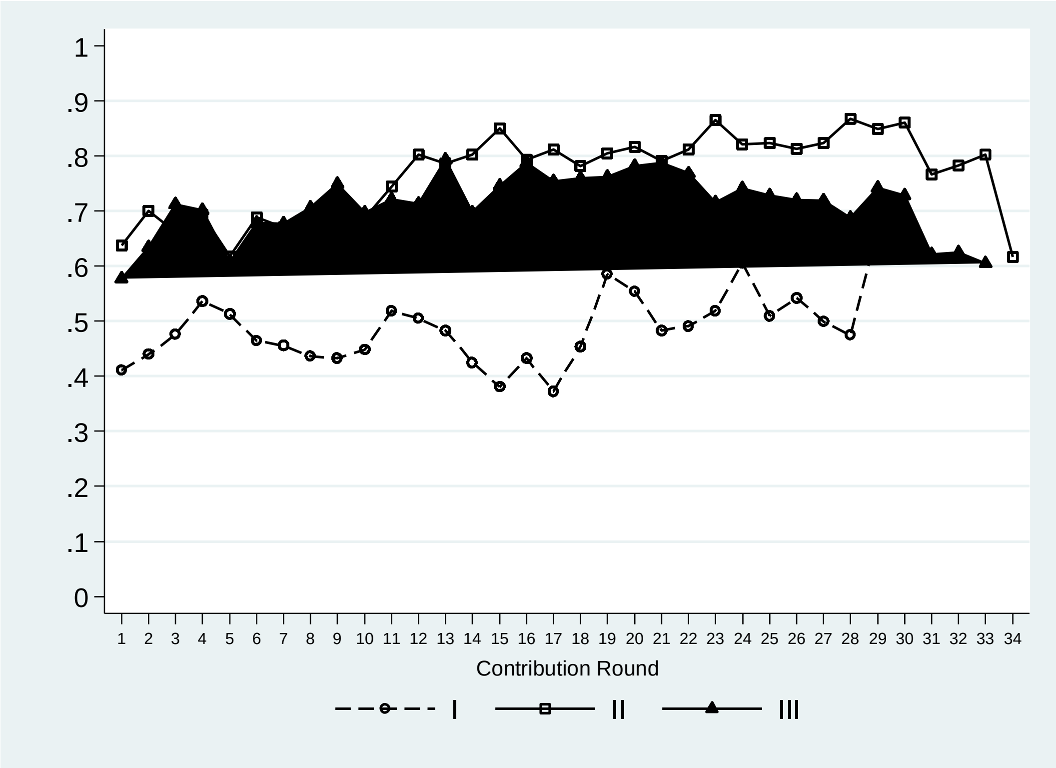

Figure 3–Actual and counter-factual predictions of contribution fractions by subjects in intermediate groups