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Promoting cooperation in resource dilemmas: Theoretical predictions and experimental evidence

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ABSTRACT

Whereas experimental studies of common pool resource (CPR) dilemmas are frequently terminated with collapse of the resource, there is considerable evidence in real-world settings that challenges 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 may significantly be 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.

1. Introduction

Social dilemmas are technically defined as interactive decision making situations in which individual rational decisions result in Pareto deficient outcomes. The Prisoner's Dilemma and the Voluntary Provision of Public Goods are notable examples. 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 functioning group of agents share the use of a common and divisible natural resource, generating a dilemma that results in resource depletion (Ostrom, Gardner, and Walker, 1994). The dilemma that each group member faces is between the individual objective of increasing 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 welfare maximizing 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, Gardner, and Walker, 1994, for an overview). While much of this research has assumed that the size and productivity characteristics of the CPR are known with precision by all group members, the role played by the environmental uncertainties characterizing most real-world commons, which potentially complicate the attainment of Pareto optimal outcomes in field settings (Ostrom, Gardner, and Walker, 1994), has not been ignored (Suleiman and Rapoport, 1988; Rapoport et al., 1992). Results from this research generally find resource requests conforming to theoretical predictions, including circumstances where 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, Gardner, and Walker, 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

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the commons, ranging from contextual factors such as non-binding communication (Ostrom, Gardner, and Walker, 1994), repeated interaction (Herr, Gardner, and Walker, 1997), sanctioning and reward systems (Ostrom, Walker, and Gardner, 1992), endogenous collective choice (Walker et al., 2000), and informational structures (Villena and Zecchetto, 2011) to individuals' preferences with social value orientations such as altruism or warm glow (Andreoni, 1995).

A common assumption underlying these experimental studies is that the problems agents are facing in managing CPRs are concerned strictly with appropriation. While this assumption is invoked to gain analytical tractability (Ostrom, Gardner, and Walker, 1994), it detracts attention from other forms of social and economic interdependencies present in natural settings. As emphasized by Gardner, Ostrom, and Walker (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 inextricably linked together may be found in field studies examining the local governance of rice farming and fishing communities (Berkes, 1986), groundwater users (Blomquist, 1992), and grazing in forest-dependent communities (Agrawal, 1992).

Perceiving these provision activities as supply-side provision problems (e.g., Gardner, Ostrom, and Walker, 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), where 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 either, the group is termed "intermediate"; as noted by Olson (1965), the public good in this case may, or may not, be provided by the group members. In cases where groups are neither privileged nor intermediate, they 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 briefly 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 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, 2013). Second, the presence of provision decisions may confer on the CPR users a "unified purpose" which has previously been 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, then 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; rather, it is accounted for 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, the present 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, 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 uncertainty about the resource size, a feature which 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. 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 and discussed in Section 4, and Section 5 concludes.

2. 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 non-cooperative game, where stage 1 has the structure of the resource dilemma under environmental uncertainty (e.g., Aflaki, 2013) regarding the resource size 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 her request. On the other hand, if the sum of group requests exceeds the size x of the resource, then the resource collapses and each individual's payoff is zero. In the latter case the game ends, whereas 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*. Each group member may contribute any fraction of her earnings or not contribute at all. 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 payoff units from that contribution, where m is a commonly known constant. 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 perceived 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 her contribution in stage 2, the expected payoff to the individual from the two-stage game is given by:

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

The subgame-perfect 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 $m \le 1/n$ 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 r_j 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.

2.1. The equilibrium solutions

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

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

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

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

To characterize the subgame-perfect equilibrium for the two-stage game, we need to combine the second-stage solutions with Eq. (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 described above of latent, fully privileged, and intermediate groups introduced by Olson (1965). We turn next to these analyses.

2.1.1. 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, Eq. (3) reduces to $r_j^* = \frac{\beta}{(n+1)}$. However, it is important to note that this solution does not constitute the equilibrium request in all first-stage cases. If $\sum_{j=1}^{n} r_j \le \alpha$, 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:

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

As noted above, when $1/n < m < 1$, the Pareto optimal solution of the second-stage game, that maximizes social welfare, 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 a single 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 and denoted by r_j^{**}) for the two-stage game is:

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

Comparison of Eqs. (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 only of stage 1.

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

For $m > 1$ in stage 2, then every group member contributes to the public good in equilibrium, i.e., $\gamma_j = \gamma_i = 1$. This result may be used in Eq. (3) to derive the Nash equilibrium request for the quadratic component in Eq. (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:

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

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

2.1.3. 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 and not contributing. Substituting the value of m into Eq. (3) allows us to derive the subgame-perfect Nash equilibrium for the two-stage game as:

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

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.

3. Experimental design and theoretical predictions

3.1. Procedures, parameters and treatments

We designed a simple experiment operationalizing the two-stage game under environmental uncertainty described by Eq. (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. A major reason for choosing these parameter values is comparison with a previous study by Rapoport and Suleiman (1992) who only studied the appropriation stage of the model using the same parameter values. 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. In the contribution phase, 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 appropriation 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, where each token was worth 2 US cents. This procedure was implemented to prevent wealth effects (i.e., effects of payoffs accumulated during the session).[1] Each experimental treatment was implemented using the *z-Tree* software, and each session lasted for about 1 h. No communication between the subjects was allowed in any of the treatments. All the experimental sessions were conducted at the Behavioral Decision Lab at the University of California, Riverside (UCR), which is a standard computerized laboratory with subject 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 for payoff contingent on performance. A total of 90 subjects participated in this experiment, 30 (six different groups) of them in each of the three treatments. Mean earnings in the experiment were \$32, including the participation fee.

Due to the different MPCR (m) of a token contribution to the public good, subjects' average earnings varied substantially across treatments. Including the participation fee, subjects earned \$45, \$33, and \$17 on average in Treatments III, II, and I, respectively. The latter compares well with subjects' average earnings of \$18 (sessions lasting for about 1 h) reported by Savikhin and Sheremeta (2013), where subjects played simultaneously a lottery contest and a standard public goods game with $m = 0.4$, which is perhaps the experimental setup most similar to ours.

3.2. Theoretical predictions

Table 1 presents theoretical predictions that are used as social welfare maximizing and equilibrium benchmarks for the analysis of the data gathered in the three treatments.[2] 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 $\Pi = 56.25$ 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 contribute to 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 ($\gamma = 1$). Conversely, individuals in the latent groups of Treatment I have a dominant strategy of zero contribution to the public good ($\gamma = 0$), 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 $\Pi = 31.25$ 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 adhere to 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

[1] Accumulated earnings during the course of play may change subjects' perceived wealth position and if subjects are *not* risk neutral (e.g., if their utility function exhibits risk aversion in a manner that is affected by wealth), such accumulated earnings may affect their decision making. The adopted payment protocol is commonly used to avoid wealth effects (e.g., Savikhin and Sheremeta, 2013), but has its own shortcomings, namely, its vulnerability to portfolio effects if subjects are not risk neutral. We thank a referee for this cautionary note, and refer the reader to Azrieli, Chambers and Healy (2013) and Cox, Sadiraj and Schmidt (2014) for recent discussions of the incentive properties of this and several other payment mechanisms commonly used in behavioral economic experiments.

[2] These numerical predictions result from the application of the model's solutions presented in Section 2, which assume that players maximize expected payoff when determining the size of their requests and contribution fractions. While different assumptions concerning players' risk preferences do not theoretically alter their dominant strategies at the second stage of the game since the mechanism is purely deterministic (i.e., the actual MPCR is equivalent to the expected MPCR), they may impact players' appropriation decisions. In fact, a generalization of the model to account for the maximization of expected utility shows that *both* the predicted equilibrium and Pareto optimal requests are lower (higher) under the assumption of (common) risk-aversion (risk-preference) by players in *all* of the considered groups. These predictions are derived in Appendix A assuming that all players have power utility functions with a *common* parameter. Because the *direction* of the change in predicted requests implied by different values for this common parameter is the same across the implemented conditions, the main conclusions in the text concerning subjects' foresight and convergence towards the respective treatment's equilibrium or socially efficient solutions are not pronouncedly affected by the shape of the subjects' utility functions *as long as* the assumption that risk preferences across subjects are the same (which, as acknowledged below, is a strong assumption, that calls for further investigations).

Table 1
Pareto optimal and equilibrium benchmarks ($n = 5$, $\alpha = 250$, $\beta = 750$).

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.

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 $\gamma = 1$. The least efficient equilibrium (hereinafter referred to as "Suboptimal NE") of Treatment II is also marked in italics, where $\gamma = 0$. Whether individuals in these intermediate groups adopt Pareto-optimal or suboptimal strategies is theoretically undetermined. This prediction 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, Battalio and Beil, 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 that view 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, where 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.[3]

4. 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.[4]

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

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

4.1. 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. *Outcomes 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.[5] 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). Table 2 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

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

[4] 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.

[5] 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.

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 in stage 1. 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 parameter values, 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 (no linking) in the two-stage decision making process.

The results in Table 2 also show that the overall variance of individual requests is lower (higher) in Treatment II (III), a pattern that tends to persist throughout the 40 rounds of play. A referee cautioned that these aggregate summary statistics may conceal substantial heterogeneity in individual requests both across subjects and over time. While an extensive analysis of individual heterogeneity is beyond the scope of the present paper, we do observe that individual responses are very dispersed in the (large) action space. In fact, the proportion of individual decisions falling within a 25% bandwidth around the mean per-period request of the respective group members accounts for only 28%, 29%, and 23% of all individual decisions by subjects in Treatments I, II, and III, respectively; the rest are symmetrically distributed around that value in Treatments I and II (about 35% are below and 35% are above), but are quite asymmetrically distributed in Treatment III where 46% are below and 31% are above.

In order to briefly evaluate whether the dispersion in individual responses may be consistently attributed to individual heterogeneity, subjects were first classified on a per-period basis as "low users", "average users", and "high users" depending on whether their requests fell below, on or above the aforementioned bandwidth; then the existence of a monotonic relation between the classification of each subject in the first and second half of the experiment was investigated through the estimation of an OLS regression without intercept taking the 20 first (second) classifications as the dependent (independent) variable (see, for example, Casari and Plott, 2003 for a similar procedure). A statistically significant unit value for the estimated coefficient in this regression provides a rough indication that subject's behavior is perfectly positively correlated between the first and second half of the experiment, suggesting consistent behavior over time. Albeit with some variation across the groups comprising each treatment, the results indicate that about 2/3 of the subjects in each treatment exhibit a remarkable consistency over time in their use patterns, supporting the view that subjects are consistently heterogeneous over time (rather than exhibiting purely random differences in behavior). Finally, a hurdle model (i.e., a statistical specification in which there are two processes: one is the process by which subjects are classified as "consistent" over time, and another is the process by which subjects request specific amounts from the CPR *conditional* on being "consistent"; see for example McDowell, 2003) was then estimated using treatment dummies, subjects' classifications depending on resource-use, and their interactions as regressors, while adjusting standard-errors for intra-group correlation and controlling for period dummies when appropriate.[6] The main summary results (available from the authors) from this exercise are that (i) no treatment effects

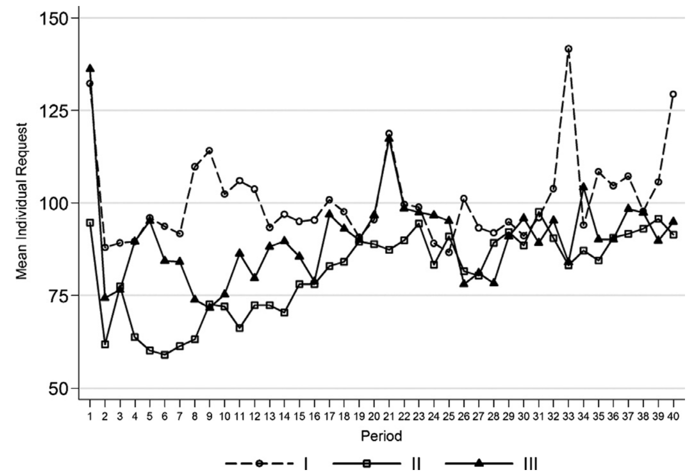

Fig. 1. Mean individual requests by treatment.

are found concerning the likelihood of being "consistent" over time, supporting the view that consistency (or heterogeneity) is intrinsic to the individual; (ii) conditional on being consistent, subjects classified as "high users" in Treatment III request more on average from the CPR than their counterparts in Treatments II and I, and the latter request more than their counterparts in Treatment II, a finding that is consistent with the results reported below.

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 then 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 the latent groups are in between the 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 the equilibrium predictions.*

Support for Result 2 comes from Fig. 1, the summary statistics displayed 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. Fig. 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 Gamal model described in Noussair, Plott, and Riezman (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. However, as t gets larger, the weight of β_2 gets larger because $(t-1)/t$ approaches unity, while the weight of β_{1i} gets smaller 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

[6] A reviewer has asked about the possibility of an endogeneity problem in the second component of the estimated hurdle model. Additional analysis (available upon request) that correlates the subjects' requested amount and the successive changes in their classification provides no evidence for endogeneity.

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.

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 for the presence of first-order individual-specific autocorrelation in our estimation procedure.

The estimated results of this model are reported in Table 3. They 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. 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 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 next to the analysis of the evolution of request behavior over time in Treatment II, we state the following result.

Result 3. *Mean requests by subjects in the 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 Fig. 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 Gamal 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 ($z = 1.192$, $p = 0.233$). 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 the 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 Fig. 1, Table 2, and the estimates in Table 3. Fig. 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.

4.2. Second-stage results

As noted previously, subjects in the three different treatments differed from one another 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 in Treatments I, II, and III, respectively.

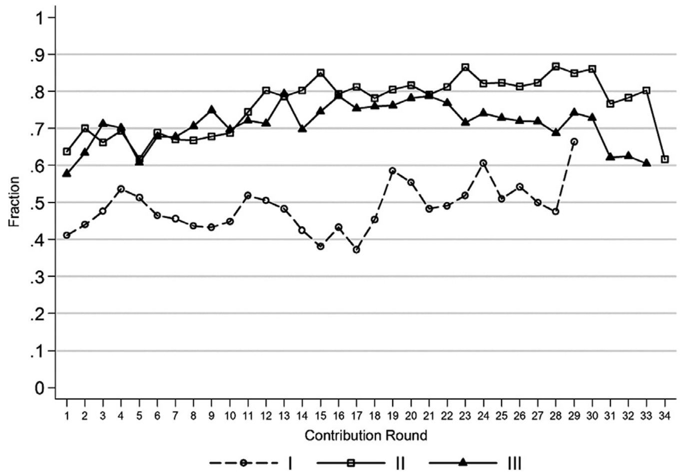

Fig. 2. Contribution as a function of subjects' endowments by treatment.

Fig. 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 may 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 the latent groups coincide with the 40–60% contribution rate previously found in linear public goods games where the unique equilibrium solution entails each player making a zero contribution.*

In addition to the results exhibited in Fig. 2, support for Result 5 comes from the summary statistics presented in the right-hand column of Table 2. Additional support is given by 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 Gamal 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 the intermediate and fully privileged groups coincide with the 60–90% contribution rate previously found in linear public goods games, where 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. 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).

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.

4.3. 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 treatment. 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 the intermediate groups strategically use their requests from the shared resource as a means to influence behavior at the contribution stage.*

Table 4 and Fig. 3 provide evidence in 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

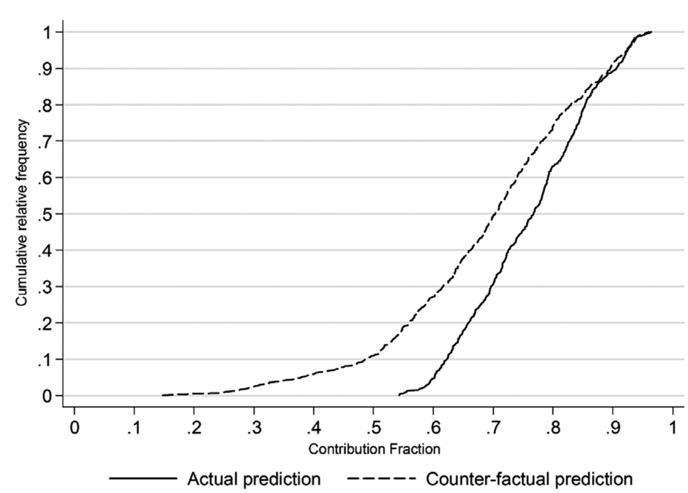

Fig. 3. Actual and counter-factual predictions of contribution fractions by subjects in intermediate groups.

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.[7] The cumulative frequency distribution of this counterfactual predicted contribution fraction is exhibited by the dashed line in Fig. 3. Also exhibited in the figure (solid line) is the predicted contribution resulting from the estimated model using the actual requests in Treatment II. Fig. 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 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%. 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 ($p < 0.0001$). In addition to the differential impact of requests on contribution behavior across treatments, these results exhibit a high degree of strategic behavior with subjects in the intermediate group taking the second-stage strategic effects of their first-stage requests into consideration when stating their requests.

5. Conclusion

The present paper proposes a two-stage model linking appropriation and provision decisions for studying resource dilemmas under environmental uncertainty. Using the framework of non-cooperative game theory, we identify circumstances in which individually rational users of shared resources make appropriation decisions that are both Pareto optimal and are in a non-cooperative equilibrium. This prediction occurs when groups are fully privileged in the sense that each of their 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 when 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, and most importantly, the mere presence of subsequent provision decisions that depend upon the potential 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 are 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, 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.

5.1. Future directions

The findings reported in the present study are limited by the assumptions underlying the two-stage model and the parameter values chosen for experimental implementation. Several directions for future research seem promising. First, assuming a uniform distribution of the unknown resource X, as in the present study, other combinations of values assigned to the two parameters, α and β, are desirable for extending the findings beyond the particular distribution chosen for the present study. Second, the assumption that the uncertain resource is commonly believed to be distributed uniformly has primarily been made to gain tractability and facilitate experimentation. It is desirable to replace it by a more general distribution that corresponds more closely to empirical data (e.g., the beta distribution that includes the uniform distribution as a special case). Third, the appropriation model that is used in the present paper, in which the payoff structure is assumed to be a step function, does not allow for continuous deterioration. It may be relaxed by considering more general deterioration models that are more suitable for capturing the *gradual* erosion process. Aflaki (2013) makes a strong case for replacing the step function of Suleiman and Rapoport (1988) by a deterioration function (e.g., exponential) that decreases in the total consumption ($\mathbf{r}$), if $\mathbf{r}$ exceeds

[7] 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.

the realized value of the randomly determined resource (x). Finally, the assumption of risk-neutrality is not essential to the model in the sense that, as shown in Appendix A, it could be replaced by other distributions about the common utility function, that would allow a systematic investigation of the effect of the degree of risk-aversion or risk-seeking on both the appropriation and contribution decisions in experiments implementing the two-stage model developed herein while measuring subjects' risk preferences.

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Appendix A. Generalization to nonlinear utility functions

Assuming symmetric players as in the text, but allowing for (common) nonlinear utility functions of, for example, the power type $u(\pi_j) = \pi_j^{\theta}, \theta > 0$, the expected utility to player j from the two-stage game is given by:

$$E(u(\pi_{jt})) = \begin{cases} (r_j - c_j + m\sum_{j=1}^{n} c_j)^{\theta} & \text{if } \sum_{j=1}^{n} r_{jt} \le \alpha \\ (r_j - c_j + m\sum_{j=1}^{n} c_j)^{\theta} \times Prob(\sum_{j=1}^{n} r_{jt} \le st) & \text{if } \alpha < \sum_{j=1}^{n} r_{jt} \le \beta \\ 0 & \text{if } \sum_{j=1}^{n} r_{jt} > \beta \end{cases}$$

Using the notation in the text, and differentiating the quadratic component in (1') with respect to r_j and equating the result to zero, yields after simplification:

$$\theta\left[r_j^*(1+(m-1)\gamma_j) + m\sum_{i\neq j}\gamma_i r_i^*\right]^{(\theta-1)}(1+(m-1)\gamma_j) \times \left(\beta - r_j^* - \sum_{i\neq j} r_i^*\right) = \left[r_j^*(1+(m-1)\gamma_j) + m\sum_{i\neq j}\gamma_i r_i^*\right]^{(\theta)}$$

Assuming symmetry, so that $r_j^* = r_i^*$, and simplifying, the first-stage equilibrium request is then given by:

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

At the outset, it can easily be verified that, irrespective of the θ value, the equilibrium predictions at the contribution stage depend only on the value of m, remaining the same as those described in the text for the case of "latent", "intermediate", and fully "privileged" groups. Thus, in the case of "latent" groups (where, in equilibrium, $\gamma_j = \gamma_i = 0$), the equilibrium solution is:

$$r_j^* = \frac{\beta\theta}{(n\theta+1)}$$

In the case of fully "privileged" groups (where, in equilibrium, $\gamma_j = \gamma_i = 1$), the solution is:

$$r_j^* = \frac{\beta\theta}{n(\theta+1)}$$

which, as in the text, coincides with the socially efficient solution for all types of groups. In the case of "intermediate" groups (where, in equilibrium, $\gamma_j \in [0-1]$), the solution is:

$$r_j^* = \frac{\beta\theta}{(n\theta+1) + \sum_{i\neq j}\gamma_i}$$

It can now be verified that these solutions are equal to the solutions derived in the text if $\theta = 1$ (risk neutrality), and that, in each case, equilibrium (and socially efficient) requests are lower under the assumption of (common) risk-aversion ($0 < \theta < 1$), and higher under the assumption of (common) risk-preference ($\theta > 1$) in comparison to the predicted risk-neutral requests.

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