**Bonus and Penalty in Common Pool
Resource Dilemmas under Uncertainty**

**Amnon Rapoport
and
Wing Tung Au**

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Amnon Rapoport

Hong Kong University
of Science and Technology

Wing Tung Au

The Chinese University
of Hong Kong

Please address all correspondence to:

Amnon Rapoport
Department of Marketing
Hong Kong University of Science and Technology
Clear Water Bay
Kowloon, Hong Kong

Phone: 852-2358-7719
Fax: 852-2358-2429
Email: mkamnon@ust.hk

Abstract

In a sequence of studies, Budescu, Rapoport, and Suleiman investigated a class of common pool resource (CPR) dilemmas characterized by the presence of both strategic uncertainty and environmental uncertainty about the size of the CPR. We extend this research--both theoretically and experimentally--in two different ways. In the bonus CPR dilemma, a bonus is given to the agent(s) who request the least; and in the penalty CPR dilemma, a penalty is imposed on the agent(s) who request the most. Under equilibrium play, we show that the bonus treatment decreases total group request, whereas the penalty treatment increases it. Our experimental results do not support this prediction. Rather, both treatments increase the rate of provision, and the penalty treatment is more effective in reducing individual requests than the bonus treatment.

Common pool resource (CPR) dilemmas constitute a class of social dilemmas in which individual rationality results in Pareto deficient outcomes that are not at all desirable for the group. The defining characteristics of CPR dilemmas have been stated by Gardner, Ostrom, and Walker (1990) and summarized briefly by Budescu, Rapoport, and Suleiman (1995). The conflict that each group member or *appropriator* (Plott & Meyer, 1975) faces in CPR dilemmas is between the individual objective of harvesting as large a share of the CPR as possible, in an attempt to increase individual payoff, and the collective goal of achieving a Pareto efficient outcome. CPR dilemmas have been investigated both theoretically and experimentally by economists and psychologists (e.g., Gardner et al. 1990; Hackett, 1992; Hackett, Schlager, & Walker, 1994; Ostrom, Walker, & Gardner, 1994; Samuelson & Messick, 1986a, 1986b; Samuelson, Messick, Rutte, & Wilke, 1984; Taylor & Ward, 1982). A common assumption underlying these studies is that the size of the CPR or the mechanism that replenishes the exhaustible resources, if one exists, are commonly known.

The plausibility and generality of this assumption have been questioned by Suleiman and Rapoport (1988), who argued that most CPR dilemmas occurring in practice are characterized by uncertainty rather than certainty about the size of the CPR. For example, the exact number of whales in the Pacific ocean, the volume of underground water reserves in arid lands, or the number of endangered species (e.g., the Bengal tiger) are not known with precision. Rather, many, if not most CPR dilemmas are characterized by both environmental uncertainty about the CPR size and strategic (or social) uncertainty about the harvesting decisions of the other group members.

The SCPR Game

To study the effects of these two sources of uncertainty simultaneously, Suleiman and Rapoport (1988) devised a (standard) CPR dilemma game, called the SCPR, that is characterized as follows: The SCPR is a single-stage non-cooperative n-person game in

which a group N of n agents can appropriate an exhaustible CPR whose exact size, denoted by x , is not known with precision. Rather, only the distribution of x is assumed to be commonly known. Each player j ($j \in N$) may request any non-negative amount r_j from the CPR. The individual payoffs, denoted by p_j , are determined by comparing the total group request $r = \sum_{j=1}^n r_j$ with the realized value of the resource x :

$$p_j = \begin{cases} r_j, & \text{if } r \leq x \\ 0, & \text{if } r > x. \end{cases} \quad (1)$$

The payoff scheme in Eq. (1) is designed to capture a basic feature of exhaustible CPR dilemmas in which overuse of the resource destroys its value. Although admittedly extreme, this payoff rule accounts for a basic characteristic of a variety of ecological systems (e.g., lakes, fisheries, rivers) which can be exploited up to some critical (threshold) level while maintaining their integrity and retaining much of their use value (e.g., Taylor & Ward, 1982). Once the exploitation level exceeds the threshold, which is often assessed by private organizations concerned with the environment or governmental agencies in charge of the environment (e.g., the EPA in the USA), the resource value drops catastrophically.

The experimental studies conducted jointly by Budescu, Rapoport, and Suleiman (Budescu, Rapoport, & Suleiman, 1992, 1995; Rapoport, Budescu, & Suleiman, 1993; Suleiman, Rapoport, & Budescu, 1998) have all assumed that the CPR is distributed uniformly on some closed interval $[\alpha, \beta]$. This assumption has been made to simplify the experimental task, as the uniform distribution is most easily explained to the subjects. To prevent unreasonable requests, most of the experimental studies have also limited the individual requests by requiring that $r_i \leq \beta$.

The Equilibrium Solution under Simultaneous Play

Under the simultaneous protocol of play, in which individual requests are made simultaneously and anonymously, the symmetric Nash equilibrium solution for risk-neutral agents is given by (Rapoport & Suleiman, 1992):

$$r_j^* = \begin{cases} \alpha/n, & \text{if } \alpha > n(\beta - \alpha) \\ \beta/(n + 1), & \text{if } \alpha \leq n(\beta - \alpha), \end{cases} \quad (2)$$

where r_j^* is the equilibrium request of agent j . For generalizations to other commonly shared attitudes to risk (e.g., power utility functions of the form $u(p_j) = (p_j)^\zeta$), see Rapoport and Suleiman (1992) and Budescu et al. (1995).

The equilibrium solution has several testable implications. First, Eq. (2) implies that the equilibrium request r_j^* is a piecewise linear function, which first decreases and then increases as the CPR range $\beta - \alpha$ for mean preserving uniform distributions increases. The “kink” point, α^* , is the solution of the equality $\alpha = n(\beta - \alpha)$. It follows then that, in equilibrium, the n individual requests will be granted with certainty if $n(\beta - \alpha) < \alpha^*$. They will only be granted probabilistically if $n(\beta - \alpha) \geq \alpha^*$. A second and related implication is that as the CPR range $\beta - \alpha$ increases beyond a certain threshold, the individual requests will increase too. If $\alpha^* \leq n(\beta - \alpha)$, then the total group request $n\beta/(n + 1)$ will approach the upper limit of the resource distribution, β , as $n \rightarrow \infty$. Consequently, the probability that the individual requests are granted, which is given by $\frac{\beta - n\beta/(n + 1)}{\beta - \alpha}$, approaches zero as $n \rightarrow \infty$. Thirdly, the equilibrium solution is Pareto deficient. Assuming, as before, symmetry and risk-neutrality on the part of all the n agents, the Pareto optimal request of agent j in the case of resource uncertainty, denoted by r_j^{**} , is given by

$$r_j^{**} = \begin{cases} \alpha/n, & \text{if } 2\alpha > \beta \\ \beta/2n, & \text{if } 2\alpha \leq \beta. \end{cases} \quad (3)$$

A comparison of Eqs. (2) and (3) shows that $r_j^{**} = r_j^*$ if $\alpha > n(\beta - \alpha)$, but that $r_j^{**} < r_j^*$, otherwise.

To illustrate those implications, assume that $\alpha = 0$, $\beta = 1000$, and $n = 5$. Equation (2) implies that $r_j^* = 1000/6 = 166.67$, and that the probability that the n individual requests will be granted is

$$\frac{\beta - n\beta/(n+1)}{\beta - \alpha} = \frac{1000 - 5000/6}{1000} = 0.167$$

If we change the number of group members from 5 to 25, keeping the same values of α and β , the probability of granting the equilibrium requests decreases from 0.167 to 0.038. The corresponding individual requests that maximize total group payoff when $n = 5$ are $r_j^{**} = 100$, and the probability that the individual requests will be granted, which holds for any value of n , increases threefold from 0.167 to 0.5.

Previous Experimental Results

Experimental results have provided qualitative support for the equilibrium predictions. For example, Rapoport and Suleiman (1992a) reported results from a SCPR game played under the simultaneous protocol of play with $n = 5$, an expected value of the CPR $\mu = (\alpha + \beta)/2 = 500$, and five values of the CPR range, namely, $\beta - \alpha = 0, 250, 500, 750$, and 1000. When $\beta - \alpha = 1000$ (implying that $\alpha = 0$ and $\beta = 1000$), the observed mean individual request was 171.6 (compared to the equilibrium request of 166.67). In another study which used a different design, Rapoport, Budescu, Suleiman, and Weg (1992) reported an observed mean request of 188.3 for the same values of $n = 5$, $\alpha = 0$, and $\beta = 1000$.

These results, both theoretical and experimental, are rather discouraging. They suggest that under the payoff rule in Eq. (1), risk-neutral players in general will not solve the dilemma. Rather, as predicted by the equilibrium solution, they will increase their requests once the CPR range exceeds some low threshold value, and thereby decrease the probability

that their requests will be granted as well as decrease their expected payoffs. One implication of these results is that players in the SCPR game should be willing to pay in order to reduce or completely eliminate the uncertainty about the value of the resource. To exemplify this implication, consider three CPR range conditions, namely 1) $\alpha = \beta = 500$, 2) $\alpha = 250$ and $\beta = 750$, and 3) $\alpha = 0$ and $\beta = 1000$, where in all three conditions $n = 5$. In equilibrium (Eq. 2), player j should request $r_j^* = 100, 125$, and 166.67 in conditions 1, 2, and 3, respectively, with corresponding expected payoffs equal to $100, 31.25$, and 27.78 . Therefore, player j should be willing to pay up to $31.25 - 27.78 = 3.47$ in order to reduce the CPR range from 1000 to 500 , and up to $100 - 27.78 = 72.22$ in order to completely eliminate the uncertainty about the CPR in condition 3. Similarly, players in the SCPR game should be willing to pay in order to allow binding and enforceable agreements about the individual requests. The individual requests that maximize the expected group (and, consequently, individual) payoff in conditions 1, 2, and 3 above are $r_j^{**} = 100, 75$, and 100 , respectively. The expected payoffs associated with these requests are $100, 56.25$, and 50 . Therefore, player j should be willing to pay up to $50 - 27.78 = 22.22$ to allow for the possibility of binding and enforceable agreements in condition 3, and up to $56.25 - 31.25 = 25$ in condition 2. All of these implications are yet to be tested experimentally.

In general, CPR dilemmas are encountered in environments in which binding and enforceable agreements are not possible and uncertainty about the exact size of the resource cannot be reduced. A possible way to weaken the force of the dilemma—a mechanism that we explore in the present paper—is to modify the payoff rule by introducing an outside agency (e.g., the government) that either reinforces *relatively low* requests or punishes *relatively high* requests. We explore below both theoretically and experimentally two alternative payoff schemes, one providing a bonus to the agent or agents who make the smallest request, and the other imposing a penalty on the agent or agents who request the

most. Under both payoff rules, the bonus is provided or the penalty is imposed relative to the requests of the *other* group members rather than in comparison to some exogenously determined threshold value.

The paper proceeds as follows. In the next section we introduce the two alternative payoff rules, construct their equilibrium solutions, and compare them to each other as well as to the equilibrium solution for the SCPR game. Following the theory section, we present and discuss results from two separate experiments designed to investigate decision behavior under these two new payoff rules. The final section compares these results to those obtained under the payoff rule of the SCPR game, and then discusses the implications of the results.

Theory

CPR Games with Bonus (BCPR)

The BCPR game is identical to the SCPR game except for the following change in the payoff function (Eq. 1):

$$p_i = \begin{cases} 0, & \text{if } \sum_{j=1}^n r_j > x \\ r_i, & \text{if } \sum_{j=1}^n r_j \leq x \text{ and } r_i \neq \min\{r_j\} \\ r_i + b/m, & \text{if } \sum_{j=1}^n r_j \leq x \text{ and } r_i = \min\{r_j\} \end{cases}$$

where b ($\alpha \geq b \geq 0$) is a non-negative bonus and m ($1 \leq m \leq n$) is the number of players requesting the minimum and thereby sharing the bonus equally.

Equilibrium Analysis

We differentiate between the cases $\alpha = \beta$ (resource certainty) and $\alpha < \beta$ (resource uncertainty). Without loss of generality, we assume that $r_1 \geq r_2 \geq \dots \geq r_n$. Consider first the case of resource certainty.

Proposition 1

In the case of resource certainty, the n requests $r^*_1, r^*_2, \dots, r^*_n$ are in equilibrium if

$$\sum_{i=1}^n r^*_i = x \text{ and either}$$

$$1) \quad (r^*_1, r^*_2, \dots, r^*_{n-2}, r^*_{n-1} \geq r^*_n + b, r^*_n > 0),$$

or

$$2) \quad (r^*_1, r^*_2, \dots, r^*_{h-1}, r^*_{h-1} \geq r^*_h \geq b/(n-h+1), r^*_{h+1} = r^*_{h+2} = \dots = r^*_n = 0),$$

where $h = 1, 2, \dots, n-1$.

Proof: See Appendix.

The case of resource certainty allows for multiple equilibria. To illustrate Proposition 1, consider the case where $n = 5$, $\alpha = \beta = x = 500$, and $b = 40$. The following vectors of requests are all in equilibrium: (108, 108, 108, 108, 68), (125, 125, 125, 125, 0), (320, 100, 40, 40, 0), (400, 85, 15, 0, 0), (489, 11, 0, 0, 0), and (500, 0, 0, 0, 0), whereas the following vectors of requests are not in equilibrium: (100, 100, 100, 100, 100), (150, 150, 110, 60, 30), and (400, 90, 10, 0, 0). In particular, the introduction of a positive bonus forces asymmetry on the equilibrium requests. Consequently, symmetry in requests can no longer serve as a natural focal point (Schelling, 1960) for resolving the coordination problem caused by the multiplicity of the equilibria. With the absence of other coordination devices, the difficulty of solving the dilemma by tacit coordination is considerably enhanced.

An exception is provided by the “symmetric” equilibrium profile, which equalizes the payoffs (rather than the requests) of the n players

$$((x + b)/n, (x + b)/n, \dots, (x + b)/n, [x - b(n - 1)]/n).$$

The “symmetric equilibrium” for the example above is the vector of requests (108, 108, 108, 108, 68). There are n such “symmetric” equilibria in which one of the n agents requests the minimum.

Consider next the case of resource uncertainty in which the CPR x is distributed uniformly over the interval $[\alpha, \beta]$. We focus on “symmetric” equilibria in which the expected payoff of the n players is the same.

Proposition 2

In the case of resource uncertainty, if all the n requests $r_1, r_2, \dots, r_n$ are positive, they are in equilibrium if

$$r_j^* = \begin{cases} (\alpha + b)/n, & \text{if } (n + 1)\alpha + b > n\beta \\ (\beta + b)/(n + 1), & \text{if } (n + 1)\alpha + b \leq n\beta \end{cases} \quad (4)$$

for $j = 1, 2, \dots, n - 1$, and

$$r_n^* = r_j^* - b.$$

Proof: See Appendix.

Comparison of Eqs. (2) and (4) shows that the equilibrium solution for the BCPR game reduces to the one for the SCPR game when $b = 0$. One implication of the solution is that the individual request should first decrease linearly and then increase linearly in the CPR range $\beta - \alpha$ when the expected value of the resource distribution, μ , is held constant. A second implication is that the introduction of a positive bonus into the dilemma game *lowers* the total group request. For the BCPR game, we have

$$r = \sum_{i=1}^n r_i = \begin{cases} \alpha, & \text{if } (n + 1)\alpha + b > n\beta \\ \frac{n\beta - b}{n + 1}, & \text{if } (n + 1)\alpha + b \leq n\beta. \end{cases}$$

Therefore, when the lower inequality holds, the difference in total group request between the SCPR and BCPR games is $b/(n + 1)$. This difference becomes practically significant only if b is large relative to n . Thirdly, similar to the SCPR game, the equilibrium requests in Eq. (4) are Pareto deficient. In the case of resource uncertainty, the individual requests of risk-neutral agents that maximize expected total group payoff, r^{**}_j , are given by

$$r^{**}_j = \begin{cases} (\alpha + b)/n, & \text{if } 2\alpha > \beta - b \\ (\beta + b)/2n, & \text{if } 2\alpha \leq \beta - b \end{cases} \quad (5)$$

for $j = 1, 2, \dots, n-1$,

and $r^{**}_n = r^{**}_j - b$.

A comparison of Eqs. (4) and (5) shows that in the case of resource uncertainty, $r^{**}_j = r^*_j$ if $(n+1)\alpha + b > n\beta$, and $r^{**}_j < r^*_j$, otherwise. To illustrate this case, consider the BCPR game with $n = 5$, $\alpha = 250$, $\beta = 750$, and $b = 60$. The individual equilibrium requests computed from Eq. (4) are (135, 135, 135, 135, 75) with a total group request of 615. In contrast, the individual requests that maximize the expected total group payoff (Eq. 5) are (81, 81, 81, 81, 21) with a total group request of 345, which is considerably smaller than 615. The expected payoff in the former case is equal to 36.45, whereas the expected payoff in the latter case (65.61) is higher by 80 percent.

CPR Games with Penalty (PCPR)

The PCPR game is identical to the basic SCPR game except for the following change in the payoff function (Eq. 1):

$$p_i = \begin{cases} 0, & \text{if } \sum_{j=1}^n r_j > x \\ r_i, & \text{if } \sum_{j=1}^n r_j \leq x \text{ and } r_i \neq \max \{r_j\} \\ r_i - p/m, & \text{if } \sum_{j=1}^n r_j \leq x \text{ and } r_i = \max \{r_j\} \end{cases}$$

where p ($0 \leq p \leq \alpha$) is a non-negative penalty and m ($1 \leq m \leq n$) is the number of agents requesting the maximum and sharing the penalty among them.

Equilibrium Analysis

As before, we differentiate between the two cases of resource certainty ($\alpha = \beta$) and resource uncertainty ($\alpha < \beta$), and assume without loss of generality that $r_1 \geq r_2 \geq \dots \geq r_n$.

Consider first the case of resource certainty.

Proposition 3

In the case of resource certainty, the n requests $r^*_1, r^*_2, \dots, r^*_n$ are in equilibrium if

$$\sum_{i=1}^n r^*_i = x \text{ and } r^*_1 \geq r^*_2 + p.$$

Proof: See Appendix.

Several comments about this solution are warranted. First, note that similarly to the solution to the BCPR game, the introduction of penalty in the PCPR game forces asymmetry in the equilibrium requests. Similarly, and also like the BCPR game, the PCPR game under certainty has multiple equilibria. For example, consider the case where $n = 5$, $\alpha = \beta = x = 500$, and $p = 40$. Then, the following vectors of individual requests are all in equilibrium: $(500, 0, 0, 0, 0)$, $(270, 230, 0, 0, 0)$, $(240, 200, 60, 0, 0)$, and $(132, 92, 92, 92, 92)$. The last equilibrium solution is “symmetric” in the sense of yielding the same payoff to all the n agents. In the general case, this “symmetric” solution is given by

$$([x + p(n - 1)]/n, (x - p)/n, \dots, (x - p)/n).$$

Note, however, that equality in payoffs does not imply that the requests are in equilibrium. For example, in the following vector of requests the n players receive the same payoff, but the individual requests are not in equilibrium: $(112, 112, 92, 92, 92)$.

Consider next the case of resource uncertainty.

Proposition 4

In the case of resource uncertainty, if all the n requests $r_1, r_2, \dots, r_n$ are positive, they are in equilibrium if

$$r^*_j = \begin{cases} (\alpha - p)/n, & \text{if } (n + 1)\alpha - p > n\beta \\ (\beta - p)/(n + 1), & \text{if } (n + 1)\alpha - p \leq n\beta \end{cases} \quad (6)$$

for $j = 2, 3, \dots, n$, and

$$r^*_1 = r^*_j + p.$$

Proof: See Appendix.

Similarly to the BCPR game, a comparison of Eqs. (2) and (6) shows that, as one would expect, the equilibrium solution for the PCPR game reduces to the one for the SCPR game when $p = 0$. Additionally, if the uncertainty about the resource is increased in a mean-preserving resource distribution, the individual equilibrium requests first decrease linearly and then increase linearly. Unlike the BCPR game, Eq. (6) implies that the introduction of a positive penalty for excessive request from the CPR *increases*, rather than decreases, the total group request. For the PCPR game, Eq. (6) implies that

$$r = \sum_{i=1}^n r_i = \begin{cases} \alpha, & \text{if } (n+1)\alpha - p > n\beta \\ \frac{n\beta + p}{n+1}, & \text{if } (n+1)\alpha - p \leq n\beta. \end{cases}$$

When the lower inequality holds, the difference in total group request between the SCPR and PCPR games is negative ($-p/(n+1)$). Finally, the equilibrium requests in the PCPR game can also be shown to be Pareto deficient.

Comparison of the Three CPR Dilemma Games

Comparison of the equilibrium solutions to the three CPR games (Eqs. 2, 4, and 6) results in several rather weak hypotheses that are experimentally testable.

Hypothesis 1. In all three dilemma games SCPR, BCPR, and PCPR, if the expected value of the resource is held constant, individual requests will first decrease and then increase as the range of the resource $\beta - \alpha$ increases.

Hypothesis 2. If the expected value of the resource is held constant, the total group request will decrease in the value of the bonus b in the BCPR game and increase in the value of the penalty p in the PCPR game.

Hypothesis 3. The group request in the PCPR game will exceed the one in the SCPR game which, in turn, will exceed the one in the BCPR game.

The theoretical implication that the imposition of an exogenous penalty for relatively high requests from the CPR increases, rather than decreases, the total group request seems counter intuitive. In addition, because of the presence of individual differences in the requests, one would expect to obtain statistically significant differences between the games only if the bonus and penalty are set at relatively large values.

Hypothesis 4. In the BCPR game, the difference between the mean request of the other $n - 1$ subjects and the request of the agent who harvests the least will be at least as large as b . In the PCPR game, the difference between the request of the agent who harvests the most and the mean request of the other $n - 1$ subjects will be at least as large as p .

Experiments

Method

Subjects. Sixty undergraduate students at the Chinese University of Hong Kong volunteered to participate in a group decision making experiment for monetary reward contingent on performance. Thirty subjects participated in Experiment B (for bonus) and thirty in Experiment P (for penalty).

Design. Both experiments were computer-controlled. Each experiment consisted of three sessions of approximately two hours each. Each session included 10 subjects who were divided on each trial into 2 different groups of $n = 5$ members each. Thus, each experiment included six groups of five subjects each for a total of 30 subjects per experiment. Although no feedback was provided at the end of each trial (see below), group membership was changed randomly from trial to trial. The subjects were only informed of their group number; they never knew who were the other group members on any particular trial.

In both experiments B and P, the actual CPR (x) was sampled randomly on each trial from one of six different uniform distributions with a common mean of $\mu = 500$ but different

ranges The six CPR conditions, which represent increasing levels of resource uncertainty, were characterized by the following parameters

<u>CPR Condition</u>	<u>α</u>	<u>β</u>	<u>CPR range</u>
1	500	500	0
2	475	525	50
3	450	550	100
4	400	600	200
5	250	750	500
6	100	900	800

These six CPR conditions were crossed with five bonus (Experiment B) or five penalty (Experiment P) values, for a total of 30 different games. The bonus and penalty assumed the values: $b = p = 0, 24, 48, 72, 96$. Each block of 30 games was iterated three times for a total of $30 \times 3 = 90$ trials played by each subject (and a total of $90 \times 30 = 2700$ trials per experiment)

Procedure. To explain the CPR game, the subjects in each experiment were asked to imagine an urn containing an unknown (x) number of coins, which could assume any integer value between two limits L (for low limit) and H (for H limit) with equal probability. On each trial, once all the subjects were publicly informed of the values of L , H , and b (for Experiment B) or p (for Experiment P), each was asked to request any number of coins from the urn not exceeding H . The subjects were instructed that their requests would be summed up by the computer, and the resulting total group request (r) would then be compared with the number of coins (x) actually sampled from the distribution for the trial. Subjects were instructed that they would be granted their requests if $x \leq r$, but receive nothing, otherwise. In addition, if $x \leq r$, the subject or subjects requesting the minimum (Experiment B) or the maximum

(Experiment P) would share equally the bonus b (Experiment B) or penalty p (Experiment P) among themselves. A detailed example was included to explain the game.

At the end of each trial, subjects were not informed of their payoff for the trial. Similarly, information about the individual or total requests of the in-group or out-group was not disclosed. To enhance motivation and reduce “noise” due to possible experimentation on the part of the subjects, the subjects were informed that their payoffs for the experiment would be equal to half of the actual outcomes of six trials randomly chosen from the 90 trials at the end of the experiment. The mean payoff per subject (in USA dollars) was \$16.8 in Experiment B and \$19.8 in Experiment P.

Before starting the experiment, the subjects were asked to answer three questions intended to verify their understanding of the game. Once they answered these questions correctly, the subjects participated in four practice trials for no money to familiarize them with the game and the mechanics of playing it. These four practice trials were then followed by the 90 experimental trials. Upon completion of the experiment, the subjects were paid their winnings individually, debriefed, and dismissed from the laboratory.

Results

Individual Requests.

Analyses of the individual mean requests and provision rates uncovered several behavioral regularities that we describe below. In general, these regularities disconfirm the first three hypotheses and only partially confirm Hypothesis 4. Evidence in support of these claims is presented below.

Hypothesis 1. Table 1 presents the mean individual requests by experiment (B or P). Within each experiment, the means are presented in terms of the experimental design that crosses six CPR ranges with five bonus/penalty values to construct 30 games. In qualitative agreement with the equilibrium predictions stated in Hypothesis 1, the marginal mean requests in Experiment P, averaged across the five penalty values, first decrease from 88.1 in the CPR

condition (500-500) to 85.7 and 85.4 in the CPR conditions (475-525) and (450-550) of intermediate range, and then increase gradually to 119.6 in the most extreme CPR condition (100-900). Similar results were reported by Budescu et al. (1995) in their test of this prediction in the SCPR dilemma game. However, we find no such support for Hypothesis 1 in Experiment B. The marginal mean requests in Experiment B (averaged across the five levels of the bonus value) increase steadily from 100.2 in the CPR condition (500-500) to 149.6 in the CPR condition (100-900), with an unpredicted dip of 110.4 in the CPR condition (250-750).

--Insert Table 1 about here--

Hypothesis 2. Examining next the marginal mean requests averaged across the six CPR conditions (bottom row of each of the two panels in Table 1), we find strong and systematic effects of both the bonus and penalty values. As predicted, the mean request decreases in the value of the penalty p from 109.7 for $p = 0$ to 83.7 for $p = 96$. However, in contrast to the same hypothesis, the mean request also decreases in the value of the bonus b from 123.8 for $b = 0$ to 106.1 for $b = 96$. The same decreasing trends were found in most of the individual CPR conditions. As shown in Table 1, they are most pronounced in the CPR condition (100-900), which has the widest range.

To study the effects of the bonus and penalty treatments in more detail, Table 2 presents for each game separately in each of the two experiments 1) the value of the mean equilibrium request (computed across the five group members) and 2) the (signed) difference between the observed mean request and the mean equilibrium request. Figure 1 depicts the mean equilibrium requests (dotted lines) and the observed mean requests (solid lines).

--Insert Table 2 and Fig. 1 about here--

Hypothesis 2 received partial support only in Experiment B. Linear regressions of the mean individual requests on the five bonus/penalty values show that the slopes of the

regression lines are negative in all 12 combinations of experiment and CPR range. In particular, the regression coefficients (slopes) assumed the values -0.058 , -0.042 , -0.224 , -0.153 , -0.229 , and -0.385 for CPR conditions (500-500), (475-525), (450-550), (400-600), (250-750), and (100-900) in Experiment B, and -0.238 , -0.143 , -0.195 , -0.163 , -0.336 , -0.460 for the corresponding six CPR conditions in Experiment P. Only the slopes of the regression lines in three CPR conditions in Experiment B ((500-500), (475-525), (450-550)) and a single CPR condition in Experiment P (475-525) were not statistically different from zero. These findings support the equilibrium predictions in Experiment B that requests decrease as bonus values increase in the CPR conditions (100-900), (250-750), and (400-600), and that requests remain unchanged in the CPR conditions (475-525) and (500-500). However, the equilibrium predictions do not fare well in Experiment P: The observed mean individual requests decreased, instead of increased, as penalty values went up in the CPR conditions (100-900), (250-750), and (400-600). The only support came from the CPR condition (475-525) that requests had negligible change across the penalty values. In summary, the generally decreasing trend of mean individual requests as both bonus and penalty values went up supports for the equilibrium solution for Experiment B but not Experiment P.

When $b = p = 0$, the only difference between Experiments B and P is in the framing of the game. To test the effects of framing, individual requests in the CPR condition (500-500), first averaged across the three within-subject replications, were subjected to a 6×2 (CPR range $\times$ experiment) ANOVA with repeated measures on the CPR range factor. The analysis yielded a significant main effect due to the CPR range ($F(5, 54) = 7.77$, $p < .05$). Further analyses show that individual requests in the CPR condition (100-900) were higher than those in the other four CPR conditions. The main effect of framing the dilemma in terms of either zero bonus value or zero penalty value was not statistically significant ($F(1, 58) = 1.22$).

Hypothesis 3. Hypothesis 3 states that the total group request in Experiment P should exceed the one in Experiment B. This hypothesis, too, was clearly rejected. With the exception of the CPR condition (500-500), Table 1 shows that the imposition of a penalty was considerably more effective in reducing individual requests than the provision of a bonus. Group requests for the cases $b = p = 0$ (resource certainty) were analyzed by a 2×6 (experiment $\times$ CPR range) ANOVA. The analysis yielded significant main effects due to experiment ($F(1, 204) = 7.54, p < .05$), and CPR range ($F(5, 204) = 11.07, p < .05$). The main effect due to experiment confirms the observation made above that the overall mean requests were higher in Experiment B (Mean request = 115.9) than in Experiment P (Mean request = 92.2). Post-hoc Tukey's HSD tests show that the mean group requests in the CPR condition (100-900) was significantly higher than that in the other five CPR conditions.

Hypothesis 4. A qualitative implication of Hypothesis 4 is that the request of the subject harvesting the minimum in Experiment B is at least b bonus points smaller than the mean request of the other four subjects. Similarly, the difference between the request of the subject harvesting the maximum in Experiment P and the mean request of the other four subjects is at least as large as the corresponding p value. This set of predictions can be tested by comparing the mean individual requests of the subjects harvesting the least (most) and those of the remaining four subjects in Experiments B (P). The results are presented in Table 3 (where the difference between the two values in each cell of the table is to be compared to the corresponding value at the top of the column). (Note that the results in Table 3 can be used to reconstruct the ones in Table 1). Of the 6×5 (CPR range $\times$ bonus value) = 30 pairs of means in Experiment B, Hypothesis 4 was supported in 26 out of 30 cases (86.7 percent). The support was weaker in Experiment P with only 11 out of 30 cases (36.7 percent) satisfying this prediction. One and three exceptions to the prediction were found in Experiment B for $b = 72$ and $b = 96$, respectively. Four, five, and five exceptions were found in Experiment P for

$p = 48$, $p = 72$, and $p = 96$, respectively. The two panels of Table 3 show that in comparison to the penalty treatment, the bonus treatment not only caused the group members to increase their requests, but it also increased the within group variability in the individual requests.

--Insert Table 3 about here--

Request provision. Another measure of the effectiveness of the bonus and penalty mechanisms is the percentage of requests that were actually provided. The equilibrium prediction and the observed percentage of requests that were actually provided in Experiments B and P are presented in Table 4. The observed percentages were subjected to a 6×5 (CPR range $\times$ bonus/penalty values) ANOVA. The results from the two experiments were analyzed separately. There was a significant main effect of the CPR range in Experiment B ($F(5, 510) = 8.06$, $p < .05$), with provision rates decreasing as resource uncertainty increased. Post-hoc Tukey's HSD tests show that the provision rate in the CPR condition 100-900 (26.7%) was significantly smaller than that in condition (500-500) (66.7%). No other effects were statistically significant in Experiment B.

In Experiment P, the main effects of the CPR range ($F(5, 510) = 10.92$, $p < .05$) and penalty value ($F(4, 510) = 12.40$, $p < .05$) as well as the interaction between these two factors ($F(20, 510) = 1.75$, $p < .05$) were all statistically significant. Provision rates decreased as resource uncertainty increased, and increased as penalty values increased. Subsequent analyses of the two-way interaction show that implementing positive penalty values was effective in increasing provision rates in all but the CPR condition (400-600). A comparison of the two panels of Table 4 shows that, because they decreased their requests compared to the requests of the subjects in Experiment B, the subjects in Experiment P were about 50 percent more successful in having their requests granted.

The effect of framing on provision rate was analyzed by comparing Experiments B and P in the case $b = p = 0$. A 2×6 (frame $\times$ CPR range) ANOVA of provision rates yielded

a significant main effect due to the CPR range ($F(5, 204) = 5.19, p < .05$). Post-hoc Tukey's HSD tests show that the provision rate in the resource distribution (100-900) was significantly smaller than that in condition (500-500). Although the overall mean provision rate under the penalty frame (52.8%) was higher than that under the bonus frame (43.5%), the difference between them was not statistically significant ($F(1, 204) = 2.03$).

Previous experimental studies of the SCPR (Budescu et al., 1992) reported provision rates of 47% and 39% for CPR ranges of (500-500) and (250-750), respectively. These baseline provision rates are considerably smaller than the overall provision rates in the corresponding resource distributions in Experiment B (67% and 43%) and Experiment P (89% and 64%), respectively. This comparison suggests that the bonus/penalty interventions were effective in increasing the provision rates in the CPR dilemma. Even when the bonus/penalty value was set at 0 in the CPR condition (500-500), the bonus/penalty frame was effective in inducing provision rates of 78% in Experiment B and 61% in Experiment P.

Effects of Learning

The equilibrium solutions presented in the previous sections are for single play of the CPR only. However, the results presented above involve iterations of the 30 games. To prevent sequential effects, group membership was randomly changed from trial to trial and outcome feedback was withheld until the end of the experiment. The design was effective in preventing learning across replications of the basic design or across trials with different games. To study the effects of experience with the CPR game, several dependent variables were examined. These included the standard deviation of the individual requests within a group, the difference between the observed standard deviation of the within-group requests and the same standard deviation under equilibrium play, the mean requests of the individual group members who requested the minimum (maximum) in their respective groups in Experiment B (P), and the standard deviation of the remaining four group members (which

equals to zero under equilibrium play). Analyses of variance that included block as one of their factors failed to show any evidence for learning for each of the dependent variables mentioned above.

Discussion

Ranging from deforestation and air pollution to over-fishing and over-grazing, CPR dilemmas have been rapidly pervading many critical aspects of our life. It is, therefore, not surprising that alternative institutions that may enhance efficiency have been studied both theoretically and experimentally. Two of the most common institutions that have been examined in cases where the incentive structure cannot be altered are communication (e.g., Ostrom, Gardner, & Walker, 1994) and sanctioning (e.g., Beckenkamp & Ostmann, 1999, Ostrom et al. 1994). Although often very effective in reducing exploitation of the commons, the former institution cannot always be implemented. The latter institution, which requires monitoring, may be quite costly. In the present study we compared to each other two additional institutions, which do not require communication or setting up external limits on the total group request. Rather, these two institutions focus on the within-group comparison of the individual requests to one another.

We have left open the question who provides the bonus or who collects the penalty. One possibility is to subsidize the bonus by collecting taxes from the n agents in the BCPR dilemma, and distribute the penalty among the n agents after it is collected in the PCPR dilemma. Yet another institution, which warrants investigation, is to use the penalty collected from the agent(s) who request the most as a bonus to be distributed among the agent(s) who request the least. When the individual requests are granted, this institution generates redistribution of the payoff among the group members based on their relative requests. Its efficiency can be determined theoretically and then studied experimentally.

Communication and sanctioning do not destroy the symmetry between the agents. In contrast, charging a penalty to the agent(s) who request the most or giving a bonus to the one(s) who request the least introduces asymmetry. Symmetry can no longer serve as a focal point for solving the CPR dilemma, even in the case where the environmental uncertainty is completely removed (condition (500, 500)). Comparison of our results with those reported in previous studies of the SCPR dilemma (in which the equilibrium solution maintains the symmetry between the players) shows that asymmetry is beneficial as it significantly increases the rate of provision. This effect is stronger in the PCPR than BCPR dilemma.

Our results (Table 4) that penalty induces higher provision rates than bonus have been obtained in all except the certainty CPR condition (500, 500) with $b = p = 0$. Table 1 also shows that the penalty treatment is more effective in reducing individual requests than providing a bonus. This result holds for the six levels of the CPR range and the five values of the bonus/penalty. They are inconsistent with the equilibrium solution (Hypothesis 3). They are also inconsistent with the experimental findings reported by Komorita and Barth (1985), who contrasted these two types of incentives in a 3-person decomposed Prisoner's Dilemma game. Their results show that the positive incentive evoked a higher level of cooperation than the negative incentive. Similar results were reported by Martichuski and Bell (1991), who used the verbal statements “good choice!” and “bad choice!” as reward for consuming little and punishment for consuming much resource from a common pool, respectively. They found that rewards could sustain the resource pool longer than punishments. However, when the resource pool was privatized, both rewards and punishments were more effective than not using any incentives. In a 10-person social dilemma game simulating a chemical pollution problem, Wit and Wilke (1990) also found that the use of rewards for cooperators and punishments for defectors, while controlling for the final payoffs to be constant, were equally effective in inducing cooperation.

Other comparisons of bonus and penalty in both individual and interactive decision making have yielded mixed results. Considering a broader view of reward and punishment that recognizes their indirect effect on observers of a person being rewarded or punished, Schnake and Dumler (1989) suggested that failure to punish undesirable behavior or over-rewarding desirable behavior may be viewed as a punishment for high performers. In the same vein, the vicarious learning (Bandura, 1977) of the proper use of punishment and reward to a person may act as a positive reinforcer of desirable behavior to an observer. The mixed empirical findings seem to suggest that the relative effects of these two types of incentives may be task and context dependent.

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Table 1

Mean Individual Requests by Experiment, CPR Range, and Bonus/Penalty Value

Experiment B

CPR Range	b = 0	b = 24	b = 48	b = 72	b = 96	Mean
(500-500)	102.8	93.2	113.1	98.6	93.2	100.2
(475-525)	109.3	113.8	111.2	110.2	106.1	110.1
(450-550)	125.3	116.5	102.8	99.9	106.7	110.2
(400-600)	124.0	117.1	111.4	114.3	107.1	114.8
(250-750)	117.8	119.2	114.6	101.0	99.4	110.4
(100-900)	163.8	159.2	154.3	146.6	123.9	149.6
Mean	123.8	119.8	117.9	111.8	106.1	115.9

Experiment P

CPR Range	p = 0	p = 24	p = 48	p = 72	p = 96	Mean
(500-500)	103.9	90.2	86.0	80.0	80.5	88.1
(475-525)	95.2	89.7	80.6	80.3	82.7	85.7
(450-550)	97.5	88.8	81.3	82.1	77.4	85.4
(400-600)	97.4	90.0	85.0	80.5	82.6	87.1
(250-750)	111.5	87.0	83.9	76.0	76.7	87.0
(100-900)	152.8	119.9	112.5	110.4	102.4	119.6
Mean	109.7	94.3	88.2	84.9	83.7	92.2

Table 2

Equilibrium Requests and Differences between Observed and Equilibrium Requests
by Experiment, CPR Range, and Bonus/Penalty Value

Experiment B

CPR Range		b=0	b=24	b=48	b=72	b=96	Mean
(500-500)	Eq. Request	100.0	100.0	100.0	100.0	100.0	100.0
	Obs. – Eq.	2.8	-6.8	13.1	-1.4	-6.8	0.2
(475-525)	Eq. Request	95.0	95.0	95.0	95.0	95.0	95.0
	Obs. – Eq.	14.3	18.8	16.2	15.2	11.1	15.1
(450-550)	Eq. Request	91.7	90.9	90.1	90.0	90.0	90.5
	Obs. – Eq.	33.6	25.6	12.7	9.9	16.7	19.7
(400-600)	Eq. Request	100.0	99.2	98.4	97.6	96.8	98.4
	Obs. – Eq.	24.0	17.9	13.0	16.7	10.3	16.4
(250-750)	Eq. Request	125.0	124.2	123.4	122.6	121.8	123.4
	Obs. – Eq.	-7.2	-5.0	-8.8	-21.6	-22.4	-13.0
(100-900)	Eq. Request	150.0	149.2	148.4	147.6	146.8	148.4
	Obs. – Eq.	13.8	10.0	5.9	-1.0	-22.9	1.2
Mean	Eq. Request	110.3	109.7	109.2	108.8	108.4	109.3
	Obs. – Eq.	13.5	10.1	8.7	3.0	-2.3	6.6

Experiment P

CPR Range		p=0	p=24	p=48	p=72	p=96	Mean
(500-500)	Eq. Request	100.0	100.0	100.0	100.0	100.0	100.0
	Obs. – Eq.	3.9	-9.8	-14.0	-20.0	-19.5	-11.9
(475-525)	Eq. Request	95.0	95.0	95.0	95.0	95.0	95.0
	Obs. – Eq.	0.2	-5.3	-14.4	-14.7	-12.3	-9.3
(450-550)	Eq. Request	91.7	92.5	93.3	94.1	94.9	93.3
	Obs. – Eq.	5.8	-3.7	-12.0	-12.0	-17.5	-7.8
(400-600)	Eq. Request	100.0	100.8	101.6	102.4	103.2	101.6
	Obs. – Eq.	-2.6	-10.8	-16.6	-21.9	-20.6	-14.5
(250-750)	Eq. Request	125.0	125.8	126.6	127.4	128.2	126.6
	Obs. – Eq.	-13.5	-38.8	-42.7	-51.4	-51.5	-39.6
(100-900)	Eq. Request	150.0	150.8	151.6	152.4	153.2	151.6
	Obs. – Eq.	2.8	-30.9	-39.1	-42.0	-50.8	-32.0
Mean	Eq. Request	110.3	110.8	111.3	111.9	112.4	111.3
	Obs. – Eq.	-0.6	-16.6	-23.1	-27.0	-28.7	-19.2

Table 3

Minimum/Maximum Request and Mean of other Four Requests by Experiment, CPR Range,
and Bonus/Penalty Value

Experiment B

CPR Range		b = 0	b = 24	b = 48	b = 72	b = 96	Mean
(500-500)	Mean	114.8	102.2	125.2	113.5	109.1	113.0
	Min.	54.7	56.9	64.7	39.1	29.6	49.0
(475-525)	Mean	117.8	124.1	123.1	124.7	123.5	122.6
	Min.	75.0	72.3	63.6	52.4	36.7	60.0
(450-550)	Mean	140.1	128.0	115.4	111.8	127.3	124.5
	Min.	66.1	70.7	52.5	52.4	24.3	53.2
(400-600)	Mean	136.1	128.4	123.6	131.9	125.9	129.2
	Min.	75.9	71.8	62.7	43.8	31.9	57.2
(250-750)	Mean	131.7	135.7	131.2	118.0	119.2	127.2
	Min.	62.1	53.3	48.2	32.9	20.1	43.3
(100-900)	Mean	188.4	184.7	178.8	174.4	150.2	175.3
	Min.	65.0	57.2	56.4	35.6	18.9	46.6
Mean	Mean	138.2	133.9	132.9	129.1	125.9	132.0
	Min.	66.4	63.7	58.0	42.7	26.9	51.6

Experiment P

CPR Range		p = 0	p = 24	p = 48	p = 72	p = 96	Mean
(500-500)	Mean	94.2	84.7	80.5	73.2	70.6	80.6
	Max.	143.1	112.1	108.0	107.4	120.0	118.1
(475-525)	Mean	90.1	84.4	74.5	73.0	73.3	79.1
	Max.	115.6	110.6	105.1	109.6	120.2	112.2
(450-550)	Mean	90.4	83.6	74.8	74.9	69.7	78.7
	Max.	125.9	109.7	107.7	110.8	108.5	112.5
(400-600)	Mean	90.2	79.7	77.9	72.2	72.7	78.5
	Max.	125.9	131.2	113.6	113.8	122.2	121.3
(250-750)	Mean	97.2	74.5	69.8	63.4	61.4	73.2
	Max.	168.9	137.0	140.4	126.6	137.8	142.1
(100-900)	Mean	130.9	94.0	89.2	90.1	74.7	95.8
	Max.	240.6	223.6	205.9	191.5	212.9	214.9
Mean	Mean	98.8	83.5	77.8	74.4	70.4	81.0
	Max.	153.3	137.4	130.1	126.6	136.9	136.9

Table 4

Observed and Equilibrium Provision Rates

Experiment B

CPR Range		b = 0	b = 24	b = 48	b = 72	B = 96	Mean
(500-500)	Equil.	100.0	100.0	100.0	100.0	100.0	100.0
	Obs.	77.8	83.3	50.0	61.1	61.1	66.7
(475-525)	Equil.	100.0	100.0	100.0	100.0	100.0	100.0
	Obs.	55.6	44.4	66.7	55.6	55.6	55.6
(450-550)	Equil.	91.7	95.7	99.7	100.0	100.0	97.4
	Obs.	44.4	66.7	66.7	66.7	61.1	61.1
(400-600)	Equil.	50.0	52.0	54.0	56.0	58.0	54.0
	Obs.	44.4	27.8	44.4	61.1	44.4	44.4
(250-750)	Equil.	25.0	25.8	26.6	27.4	28.2	26.6
	Obs.	22.2	38.9	44.4	61.1	50.0	43.3
(100-900)	Equil.	18.8	19.3	19.8	20.3	20.8	19.8
	Obs.	16.7	27.8	16.7	27.8	44.4	26.7
Mean	Equil.	64.2	65.5	66.7	67.3	67.8	66.3
	Obs.	43.5	48.1	48.1	55.6	52.8	49.6

Experiment P

CPR Range		P = 0	p = 24	p = 48	p = 72	p = 96	Mean
(500-500)	Equil.	100.0	100.0	100.0	100.0	100.0	100.0
	Obs.	61.1	88.9	100.0	100.0	94.4	88.9
(475-525)	Equil.	100.0	100.0	100.0	100.0	100.0	100.0
	Obs.	61.1	88.9	100.0	88.9	83.3	84.4
(450-550)	Equil.	91.7	87.7	83.7	79.7	75.7	83.7
	Obs.	55.6	88.9	94.4	88.9	100.0	85.6
(400-600)	Equil.	50.0	48.0	46.0	44.0	42.0	46.0
	Obs.	72.2	83.3	66.7	88.9	72.2	76.7
(250-750)	Equil.	25.0	24.2	23.4	22.6	21.8	23.4
	Obs.	38.9	66.7	50.0	88.9	77.8	64.4
(100-900)	Equil.	18.8	18.3	17.8	17.3	16.8	17.8
	Obs.	27.8	38.9	83.3	50.0	72.2	54.4
Mean	Equil.	64.2	63.0	61.8	60.6	59.4	61.8
	Obs.	52.8	75.9	82.4	84.3	83.3	75.7

Figure Caption

Figure 1. Mean requests by resource distributions and bonus/penalty values in Experiment B and Experiment P.

Mean Requests by Resource Distributions and Bonus/Penalty Values

Appendix

Proof of Proposition 1

If $\sum_{i=1}^n r_i = x$, then no player can benefit by unilaterally deviating and requesting more.

Case 1. If all the n requests are positive, ($r_i > 0$, $i = 1, 2, \dots, n$), then there must be only a single player (i.e., player n) who requests the minimum (and ends up with $r_n + b$). If there are two players who request the minimum ($r_{n-1} = r_n$), and therefore share the bonus b equally between them, then one of them can deviate, decrease his request by some $\varepsilon > 0$, and receive the entire bonus. Thus, if $r_{n-1} < r_n + b$, then player $n - 1$ can benefit by requesting $r_n - \varepsilon$ and ending up with $r_n + b - \varepsilon > r_n + b/2$.

Case 2. If only the first h requests ($h = 1, 2, \dots, n - 1$) are positive, then there are $n - h$ players who request the minimum (i.e., 0), each of whom receiving $b/(n - h)$. In this case, if $r_h < b/(n - h + 1)$, player h can benefit by deviating and requesting 0, thereby ending up with $b/(n - h + 1)$. QED

Proof of Proposition 2

In a “symmetric” equilibrium there can be only a single player (i.e., player n) who makes the minimum request and receives the bonus b .

Denote the expected payoff of player i who requests r_i by $E(r_i)$, and the total requests of all $n - 1$ players except player i by r_{-i} . Then, the expected payoff of player j ($j = 1, 2, \dots, n - 1$) is given by

$$E(r_j) = \begin{cases} r_j, & \text{if } r_j + r_{-j} \leq \alpha \\ r_j[\beta - (r_j + r_{-j})]/(\beta - \alpha), & \text{if } \alpha \leq r_j + r_{-j} \leq \beta \\ 0, & \text{if } r_j + r_{-j} > \beta. \end{cases} \quad (1)$$

The expected payoff of player n is given by

$$E(r_n) = \begin{cases} r_n + b, & \text{if } r_n + r_{-n} \leq \alpha \\ (r_n + b)[\beta - (r_n + r_{-n})]/(\beta - \alpha), & \text{if } \alpha \leq r_n + r_{-n} \leq \beta \\ 0, & \text{if } r_n + r_{-n} > \beta. \end{cases} \quad (2)$$

where $[\beta - (r_j + r_{-j})]/(\beta - \alpha) = [\beta - (r_n + r_{-n})]/(\beta - \alpha) = (\beta - \sum_{i=1}^n r_i)/(\beta - \alpha)$ is the probability that the n requests will be granted under the uniform distribution of the CPR.

If $r_j + r_{-j} \leq \alpha$, then like in the case of resource certainty, it is evident that any vector of requests $\mathbf{r} = (r_1, r_2, \dots, r_{n-2}, r_{n-1} \geq r_n + b, r_n)$, whose components satisfy the condition $\sum_{i=1}^n r_i = \alpha$ is in equilibrium. In particular, we are interested in “symmetric” equilibria in which all the n players receive the same payoff:

$$((\alpha + b)/n, (\alpha + b)/n, \dots, [\alpha - b(n - 1)]/n). \quad (3)$$

Clearly, there are n such equilibria up to a permutation of the single player who requests the minimum

. If $\alpha \leq r_j + r_{-j} \leq \beta$, an equilibrium solution is a vector $\mathbf{r} = (r_1, r_2, \dots, r_n)$ whose components satisfy $\partial E(r_i)/\partial r_i = 0$ and $\partial^2 E(r_i)/\partial r_i^2 < 0$, for $i = 1, 2, \dots, n$. Differentiating $E(r_j)$ in Eq. (1) and $E(r_n)$ in Eq. (2) with respect to r_j and r_n , respectively, and then equating the results to zero yields

$$[\beta - (r_j^* + r_{-j}^*) - r_j^*]/(\beta - \alpha) = 0, \quad j = 1, 2, \dots, n - 1 \quad (4)$$

and

$$[\beta - (r_n^* + r_{-n}^*) - r_n^* - b]/(\beta - \alpha) = 0. \quad (5)$$

It is easy to verify that the second derivatives in Eqs. (4) and (5) are negative. Note that in the “symmetric” equilibria $r_j = (n - 2) r_j + r_n$ and $r_n = (n - 1) r_j$. Substituting these two expressions in Eqs. (4) and (5) above, we obtain

$$\beta - (r_j^* + (n - 2) r_j^* + r_n^*) - r_j^* = 0.$$

$$\beta - (r_n^* + (n - 1) r_j^*) - r_n^* - b = 0.$$

Solving for r_j^* and r_n^* , we obtain

$$r_j^* = \frac{\beta + b}{n + 1} \quad (6)$$

and

$$r_n^* = \frac{\beta - nb}{n + 1} = r_j^* - b. \quad (7)$$

Combining Eqs. (3), (6), and (7), the “symmetrical” equilibrium solution has the form

$$r^*_j = \begin{cases} (\alpha + b)/n, & \text{if } \sum_{i=1}^n r_i \leq \alpha \\ (\beta + b)/(n + 1), & \text{if } \alpha \leq \sum_{i=1}^n r_i \leq \beta, \end{cases} \quad (8)$$

for $j = 1, 2, \dots, n - 1$, and $r^*_n = r^*_j - b$.

The second condition in Eq. (8) can be written as $\alpha \leq n(\beta + b)/(n + 1) - b \leq \beta$, implying that $(n + 1)\alpha + b \leq n\beta$. Consequently, Eq. (8) assumes the form

$$r^*_j = \begin{cases} \frac{\alpha + b}{n}, & \text{if } (n + 1)\alpha + b > n\beta \\ \frac{(\beta + b)}{n + 1}, & \text{if } (n + 1)\alpha + b \leq n\beta, \end{cases}$$

for $j = 1, 2, \dots, n - 1$, and $r^*_n = r^*_j - b$.

QED

Proof of Proposition 3

If $\sum_{i=1}^n r_i = \alpha$, no agent can benefit by unilaterally deviating and requesting more. There can

be only a single agent who requests the maximum. If there are h such agents, $h > 1$, with each of them paying a penalty of p/h , then any one of them can benefit by lowering her request by some ε ($\varepsilon > 0$).

Similarly, in contrast to the proposition, if $r_2 + p > r_1$, then player 1 can benefit by deviating and requesting $r_2 - \varepsilon > r_1 - p$.

QED

Proof of Proposition 4

The proof is similar to the one for Proposition 2. Under the payoff scheme of the PCPR game, the expected payoff of player j ($j = 2, 3, \dots, n$) is given by

$$E(r_j) = \begin{cases} r_j, & \text{if } r_j + r_{-j} \leq \alpha \\ r_j[\beta - (r_j + r_{-j})]/(\beta - \alpha), & \text{if } \alpha \leq r_j + r_{-j} \leq \beta \\ 0, & \text{if } r_j + r_{-j} > \beta \end{cases} \quad (9)$$

whereas the expected payoff of player 1, the one requesting the maximum, is give by

$$\begin{aligned}
& r_1 - p, & \text{if } r_1 + r_{-1} \leq \alpha \\
E(r_1) = & (r_1 - p)[\beta - (r_1 + r_{-1})]/(\beta - \alpha), & \text{if } \alpha \leq r_1 + r_{-1} \leq \beta \\
& 0, & \text{if } r_1 + r_{-1} \geq \beta.
\end{aligned} \tag{10}$$

If $r_j + r_{-j} \leq \alpha$, then any vector of requests $\mathbf{r} = (r_1 \geq r_2 + p, r_2, \dots, r_n)$ is in equilibrium

if the requests satisfy the equality $\sum_{i=1}^n r_i = \alpha$. In particular, we are interested in the

“symmetric” equilibrium that yields the same payoff to all the n agents:

$$([\alpha + p(n-1)]/n, (\alpha - p)/n, \dots, (\alpha - p)/n). \tag{11}$$

There are n such equilibria, depending on the position of the player who requests the most.

To construct the equilibrium requests when $\alpha \leq r_j + r_{-j} \leq \beta$, we differentiate Eqs. (9) and (10) with respect to r_j and r_1 , respectively, and equate the results to zero. This yields the two equations

$$[\beta - (r_j^* + r_{-j}^*) - r_j^*]/(\beta - \alpha) = 0, \quad j = 2, 3, \dots, n$$

and

$$[\beta - (r_1^* + r_{-1}) + p]/(\beta - \alpha) = 0.$$

Solving for r_j^* and r_1^* , we obtain

$$r_j^* = (\beta - p)/(n + 1) \tag{12}$$

and

$$r_1^* = (\beta + np)/(n + 1). \tag{13}$$

Combining Eqs. (11), (12), and (13), the “symmetrical” equilibrium solution has the form:

$$\begin{aligned}
r_j^* = & (\alpha - p)/n, & \text{if } \sum_{i=1}^n r_i \leq \alpha \\
& (\beta - p)/(n + 1), & \text{if } \alpha \leq \sum_{i=1}^n r_i \leq \beta.
\end{aligned}$$

for $j = 2, 3, \dots, n$, and $r_1^* = r_j^* + p$.

When the second condition above holds, $\sum_{i=1}^n r_i = (n\beta - p)/(n + 1)$, implying that $(n +$

$1)\alpha - p \leq n\beta$. Therefore, we have

$$r^*_j = \begin{cases} (\alpha - p)/n, & \text{if } (n + 1)\alpha - p > n\beta \\ (\beta - p)/(n + 1), & \text{if } (n + 1)\alpha - p \leq n\beta, \end{cases}$$

for $j = 2, 3, \dots, n$ and $r^*_1 = r^*_j + p$.

QED

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