Experimental Economics (2025), 1–24
doi:10.1017/eec.2024.6

ORIGINAL PAPER

An anatomical review of the common pool resource game

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(Received 9 October 2024; revised 19 October 2024; accepted 19 October 2024)

Abstract

Over the last four decades, a broad stream of experimental literature has been published using the Common Pool Resource (CPR) game to study how people react to congestible resources, and how to keep such resources from socially harmful overexploitation. With the goal of providing guidance to future work on this still-important paradigm, we provide a narrative review of the literature, summarizing the results for several key aspects of the experimental operationalization. We classify these aspects into two broad categories. The first describes 'environmental' assumptions on the modeled resource problem itself. This refers to aspects of the experimental environment reflecting factors such as group size, resource size and asymmetry of access, which generally constitute the nature of the dilemma. The second category involves 'institutional' issues related to how people might solve the problem, such as user communication between subjects, information about previous subjects' choices, and regulatory measures.

Keywords: Climate change; Common pool; Commons dilemma; Experiment; Harvesting

JEL Codes: C9; Q0; Q2; Q3; Q5

1. Introduction

Common pool resource (CPR) problems are characterized by a *congestion externality* emerging from collective use (which we will call *harvest*) of a rival, non-excludable resource. Users of the resource obtain some net private benefit from each unit harvested, but the marginal private benefits to each decrease in the aggregate harvest by the others, which constitutes a social cost. Individually rational users who equate private marginal costs with private marginal benefits therefore overharvest the resource from the point of view of aggregate benefit, which is the source of the social dilemma known since Hardin's seminal 1968 article as the tragedy of the commons.

Real-world examples of CPR problems abound, ranging from coffee supplies in a university faculty lounge to the planet's global atmospheric carbon absorption capacity, and substantial evidence suggests that real-world users often fail to efficiently exploit such resources, sometimes with catastrophic results (e.g., Wright, 2017). The obvious ecological (in all senses of the term) relevance of CPR problems has made them a very attractive paradigm for experimental social science; the year 2021 marked the 40th anniversary since Jorgenson and Papciak (1981) published the first experimental CPR game, and each additional decade since has added more new papers than the previous.

This article presents a narrative review of this accelerating literature, covering a wide array of studies implementing experimental CPR games ($N = 123$). To the best of our knowledge, only three surveys on CPR experiments have been published to date, all focusing on narrower questions than ours. Ostrom (2006) surveyed the effect of institutions in the sense of additional rules about what users could do (e.g., communication, sanctioning and regulations). Mantilla (2018) studied the impact of environmental uncertainty (e.g., the total resource available or its regeneration rate). Finally, Djiguemde (2020) focused on the dynamics of CPR extraction.

We compare our approach to 'functional anatomy,' a sub-field of biological sciences that 'offers an attempt to exploit anatomical information as a platform from which to decipher mechanistic details of complex … processes' (Pabst et al., 2004, p. 394). In analogous fashion, we dissect the literature we review and classify it by structural component, then seek by summarizing the experimental results to elucidate what each component 'does' with respect to CPR management. Structurally, the literature can be classified into two main categories: one part studying *natural features that make the commons problem worse*, and the other *how people can make the problem easier*. We refer to the former category as 'environmental assumptions,' because it refers to (the experimental operationalization of) the natural environment in which subjects find themselves. The latter category we call 'institutional issues' because it refers to (again, experimental operationalizations of) local rules and institutions that people could implement to better address the problems they face.

The result is that while the total number of papers we review is large, so is the number of variables that they manipulate, which necessitated our narrative design rather than a more systematic attempt to address a more specific question. We hope that this presentation will be useful both to pave the way for future meta-analytic and more systematic analyses, and also to researchers interested in running replications and further experiments of this type. This review may be read in its entirety as a comprehensive introduction to the experimental paradigm; however, we also envision its usefulness to researchers interested in studying a particular dimension of the problem.

Thus, after briefly outlining our methodology and scope in section 2, in section 3 we review the results from experiments manipulating the nature and intensity of the congestion effect, as well as asymmetry in access or benefits and uncertainty on different aspects. Section 4 then delves into several assumptions about the institutions that can influence resource survival, including informal measures (communication, feedback), formal measures (privatization, exogenous quotas and punishment related), and finally democratically instituted regulations (quotas, peer punishment, leadership status).

2. Methodology and analytical approach

The relevant literature includes published and unpublished experimental studies posted between 1980 and 2021. Studies were identified using the online databases and academic web search engines Econlit, Google Scholar and ScienceDirect. We particularly built on the Cooperation Databank's extensive work collecting experimental articles on the topic (Spadaro et al., 2022). We limited the studies included according to several criteria. First, we only include experiments manipulating either 'nature' or 'institutions' within the experimental environment. Studies wholly conducted through field observation were excluded, as were those that studied purely individual covariates of CPR extraction behavior such as inherent prosociality or demographic status (e.g., student participants versus 'real people').

Second, we focus on treatments that model the interaction as a *congestion externality*. Individuals receive benefits proportional to their share of aggregate harvest, but the surplus they share is, at least over some range, falling in the sum of the individual harvest choices, according to a relationship we call the *congestion function*. Apesteguia and Maier-Rigaud (2006) identify the first element with the rivalrousness of the modelled resource, in distinction to public goods games in which a collective surplus is shared equally regardless of individual choices, and show that while in linear-surplus cases the two may be equivalent, this equivalence does not generally hold. The second element is the 'public good' component of a CPR that generates the tragedy of the commons, and makes the interaction different from simply sharing a pie. It does not, however, imply that CPR games are *social dilemmas*

https://doi.org/10.1017/eec.2024.6 Published online by Cambridge University Press

as defined by Liebrand (1983), that is, a game in which each player has an individually optimal strategy such that the combination of those strategies results in outcomes that are sub-optimal for each, when collectively played.[1] Indeed, this characterization is neither sufficient (as evidenced by the non-equivalence with public goods games) nor (as we will see presently) even necessary to identify CPR games as we define them.

The great majority of the papers we review can be seen as variations on one of two game forms, known as the *investment game* and the *request game*. Details of these games can be found in Appendix A. They differ in important ways. The investment game is a proper social dilemma in the sense described above, usually with a non-linear congestion function generating interior Nash equilibrium and Pareto-optimal individual harvest levels such that the Nash level is higher than the Pareto optimal, and results in lower payoffs for all players. The request game, by contrast, is an N-person coordination game in structure, with a fixed surplus S and payoffs equal to harvest rates x_i, $i = 1..N$ if $\Sigma\ x_i \leq S$ and zero otherwise. This yields a continuum (to the granularity of action) of efficient equilibria including (usually) one symmetric one such that $x_i = S/N$ for all i. In addition to their strategic differences, these games also differ in framing; 'requests' and 'investments' are both 'harvests,' exactly analogous in payoff terms, but the words have quite different connotations. However, they share our defining characteristics that (a) payoff is proportional to harvest, and (b) aggregate overharvest reduces all payoffs. Notice that in this sense the request game can also be seen as a simplification of the investment game. In the canonical investment game, the congestion function is quadratic, resulting in complex calculations required to identify the *theoretical* Nash and Pareto harvest rates; reaching them in practice is likely even harder, at least in one shot. In the request game, congestion is a step function that annihilates all surplus when aggregate harvest crosses a threshold, making the equilibrium condition ($\Sigma x_i = S$) and symmetry conditions considerably more salient.

As a final note on the structure of the games we consider, these static, one-shot games can be repeated as stage games in a repeated setting to allow convergence to some kind of "equilibrium, or to generate a *dynamic CPR* by letting the congestion function in any period (for instance, either the peak of the parabola in an investment game or S from a request game) itself depend on the aggregate harvest from previous periods. The latter case clearly introduces another, intertemporal dimension of congestion to the environment, corresponding to what Ostrom et al. (1994) call *provision* as opposed to *appropriation* problems. Appropriation problems concern the efficient use by harvesters of an existing, given resource, while provision problems in a CPR context describe action that affects the resource 'abundance.' Ostrom et al. (1994) further distinguish between 'demand-side' provision problems, which correspond to the dynamic CPR games described above, where harvester actions in themselves also affect the resource, and 'supply-side' provision, which give participants the opportunity to engage in a preliminary public good provision task that determines the subsequent CPR resource. This last category is mainly covered in our review by *irrigation games*.

With regards to our analytical approach, we classify the effect of design choices qualitatively, by the number of reviewed papers finding that a given factor increased or decreased harvest rates. In this line, note that because the economic problem in managing a CPR is one of individually rational *overharvesting*, an increase in harvest rates generally corresponds to worse outcomes in terms of overall average payoffs. Therefore, in general, results finding reductions in harvest rates are interpreted as 'improvements,' while those indicating increased rates will be making the problem 'worse.' However, it is important to note that some kinds of changes – such as reducing the number of extractors for a fixed pool of resources or increasing the pool size for a fixed group – actually relax the commons dilemma. In these cases, the socially optimal (in the sense of aggregate payoff-maximizing) individual

[1] For further reviews on the topic, see, e.g., Kollock (1998), Ledyard (1994) and Messick and Brewer (2005).

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Table 1 Summary of anatomical variations, and their impact on harvesting

Design component	Increases harvest	Null	Decreases harvest	Total
(a) Environmental determinants of congestion				
Resource uncertainty	16	–	–	16
First mover position	9	–	–	9
Larger groups	2	5	–	7
Smaller resource	2	–	1	3
Probabilistic loss	–	2	3	5
Slow regeneration rate	–	–	3	3
	29	7	7	43
(b) Institutional issues				
Communication	–	–	24	24
Endogenous quotas	–	–	3	3
Elected (vs. appointed) authority	–	–	3	3
Exogenous punishments	–	–	3	3
Feedback on resource use	–	1	6	7
Warning messages	1	–	2	3
Exogenous quotas	–	4	2	6
Endogenous punishments	–	5	–	5
	1	10	45	56

Note: This table summarizes the impacts on harvesting for effects studied in at least three papers. One paper in the Feedback on the resource use is marked as a null result, as the authors found conflicting evidence in their two treatments.

extraction rate also changes, so it is important to keep in mind not just how behavior responds, but how it responds with respect to the efficient level.

The overall picture for elements on which at least three comparable papers was found is summarized in Table 1. For each component of the design, Table 1 shows the number of identified papers that find an effect increasing harvest rates, decreasing harvest rates, and with no effect. Panel (a) contains environmental elements of the commons problem. Note that these are turned such that each is a potential obstacle to successful resource management, and are ordered from the strongest to weakest detrimental (i.e., harvest-increasing) impact. Panel (b) shows the institutional factors that have been studied to alleviate the commons problem, and is ordered from those with the strongest to weakest improvement (harvest-reducing) effect. Several interesting points emerge. First, in terms of the environmental determinants of congestion, we see that large groups weakly increase harvest rates, while smaller resources, which yields the same effective result per capita, have somewhat of a similar effect. This asymmetry comes out even more with respect to uncertainty. Uncertainty about the resource size leads conclusively to higher individual harvest rates, while that concerning the number of harvesters decreases harvest rates (although admittedly in a small set of studies). We will discuss these results further below.

Turning to the institutional issues, the most interesting asymmetry may have to do with *self-governance*. Communication, endogenous quotas and elected authority – all related to experimental self-regulation – strongly decrease harvest rates, while more top-down features such as exogenous feedback on the state of the resource, warning messages and harvest quotas have a more mitigated impact. However, the least effective measure, endogenous (i.e., peer) punishment, is also 'bottom up' but has no strong impact at all. Similarly, exogenous punishment is by nature top-down, and is found to be very effective at decreasing harvests.

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3. Environmental assumptions on the structure of the dilemma

A CPR experiment is (presumably) designed to reflect some real-world problem of rival, non-excludable use of a resource. Any such problem arguably has two central components: the environmental nature of the resource itself, and the measures that may be available to keep people from overharvesting it. Consider the canonical example of fish in a lake. The most obvious environmental considerations will be the number of fish and the number of fisherfolk trying to catch them. But the literature also points out the importance of factors such as the rate at which the fish reproduce and the ease with which any particular person can catch a given number of fish. We classify all these as environmental assumptions because they correspond to model parameters that do not reflect direct social decisions. In this section we review the literature on experiments directly manipulating such factors. In section 4, we will turn to formal and informal agreements and constraints on what people are 'allowed to do' – and the potential punishments for not respecting them – which collectively represent institutional factors more under some kind of social control.

3.1. Group size: The number of fishers

It has long been a foundational conjecture that collective action is made difficult by large groups (Olson, 1965), and the conjecture received early support in some experimental contexts. For CPR problems, it seems like a direct corollary that if 'too many fishers in the same lake' is the problem, then adding more fishers should make the problem worse. Such an effect might operate through many channels. Large groups seem likely to amplify a 'diffusion of responsibility' (Darley & Latané, 1968) as each harvester's choice is smaller relative to the collective outcome. And to the extent that commons management requires trust in others not to overexploit, large groups may also increase the probability that someone will break the trust, causing it to unravel in a kind of self-fulfilling prophecy. But the evidence for this has been perhaps surprisingly weak, and not particularly robust. Indeed, most (5/7) papers specifically manipulating this variable find no significant effects, although when the effect does exist, large groups seem to impede management of the resource (2/7).

Allison and Messick (1985) show that groups of three maintain a dynamic request game longer and earn substantially higher rewards than do groups of six. This effect diminishes with experience, and interestingly, particularly with experience harvesting from the same resource *alone*, that is, in groups of one, in a preliminary block of periods. They conclude that members of a large group cannot easily discern the relation between their own individual actions and the environmental consequences of their acts, and face more difficulties in coordination. As part of their research program on random-pool request games (see section 3.5 on studies manipulating uncertainty in the CPR environment), Budescu et al. (1995b) study one-shot request games with fixed (average) pool sizes and groups of 2, 3 and 5. Their focus is on the effect of position in *sequential requests*, where a 'group' is actually a chain, but by comparing their simultaneous baseline groups in each case, one notices that larger groups request more on average, with correspondingly higher rates of resource collapse.

However, most papers cast doubt on the strength of this group size effect. For instance, Pavitt and Broomell (2016) run a dynamic request game with group sizes between 3 and 8, and communication between rounds, under the assumption (not tested in the paper) that absent such communication, larger groups would empty the pool faster and earn less money. With communication, in any case, there was no significant correlation between group size and either outcome. Brewer and Kramer (1986) found that when the choice problem was framed as a commons dilemma so that individuals had to decide whether to take resources from a common pool, resource-use decisions were not altered by group size, although in an equivalent framing of the problem as contributions to a public good rather than extractions from a common pool, individuals in large groups kept (equivalent to extracting) more than did individuals in small groups. Janssen et al. (2011b) also run a sequential request game with supply-side provision, in the form of a Voluntary Contribution Mechanism to a

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public good determining the pool size S. Harvest from the pool is sequential as in Budescu et al. (1995b), but average earnings between the $N = 2$ and $N = 5$ groups are very similar across rounds.

Overall, despite theoretically plausible reasons that large groups may have difficulty sustaining a CPR, and *ceteris paribus* evidence that the effect does obtain, it appears to be vulnerable to many kinds of institutional variation (discussed more fully in section 4). It bears mention that the group sizes in experimental protocols show a relatively restricted range, nearly always in the single digits; the harmful effects of large groups may depend on more extreme definitions of 'larger.' But at least within the range usually studied, the literature suggests group-size effects are not insurmountable.

3.2. Resource size: Number of fish

Resource size can be thought of in some ways as the 'dual' problem to group size, but in the laboratory, where the resource is composed of abstract tokens, it is not obvious what a larger nominal resource means. One way to implement scarcity or abundance is to vary individual harvest capacities relative to the total feasible harvest for the group. Osés-Eraso et al. (2008) use a dynamic request game in which participants have an endowment to spend on harvesting a resource, which replenishes at a given rate between rounds to generate an intertemporal provision congestion externality. They define 'scarce' or 'abundant' resources with resource sizes less than, or respectively greater than, the sum of group endowments, relative to a baseline of equality. The authors find that participant behavior is responsive to scarcity in the sense of being well described by a 'limit strategy' consisting of the highest harvest rate that ensures resource survival for the full 20-period game. However, this responsiveness is imperfect, 'abundant' resources are not more likely in their setting to survive than 'scarce' ones.

Other authors test resource scarcity within-subjects by implementing larger and smaller pools with the same groups. Blanco et al. (2015) set up a request game to study how people react to exogenous changes in the availability of a shared resource (whether it is a low, medium or strong reduction) and its suddenness (whether it is sudden or progressive). In contrast to the above studies, authors found that subjects reacted to persistent and strong reductions in resource availability by increasing appropriation (becoming less cooperative), although the effect did not become statistically significant until subjects had been playing under the low resource size for over 10 rounds. Moderate changes in the resource size, given similar durations, did not significantly affect the average individual appropriation.

Pfaff et al. (2015) conducted a sequential CPR game where the pool size varied. In the first treatment, the pool size ranged from a low to high level (four rounds each of 20, then 60, then 100 units), while in the second treatment, it was the reverse (100, then 60, then 20 units). The researchers found that upstream farmers extracted more but had a lower share when faced with higher resources. Moreover, after experiencing scarcity (i.e., in later rounds of treatment (1), upstream farmers appropriated more compared to those from treatment 2 who experienced abundance.

The results therefore appear mixed. Some studies (1/3) have found that smaller pools make users more cautious and cooperative. But on the other hand, being in this situation makes some people rush the resource and make it disappear even more quickly (2/3). The within-versus between-subject variation might account for this, as might differences across samples used in those four studies; Osés-Eraso et al. (2008) ran their studies with university students, while the latter ones were run with farmers from rural Colombia.

3.3. Fast versus slow regeneration

As alluded to in section 2, one of the key environmental characteristics of the real-world resources that CPR models are arguably best suited to describe is that they are *renewable*, characterized by some natural rate of replenishment of the non-excludable, rival resource. Modeling this replenishment explicitly in an experiment induces a *dynamic* CPR dilemma, where over time, the harvest level in one period affects the resource pool size in the next. The game forms we described previously

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are therefore stage games in this repeated structure. However, the dynamic setting adds a distinct intertemporal congestion effect, which Ostrom et al. (1994) called the provision problem. In this case, a higher replenishment rate corresponds to an 'easier' social dilemma. The existent results in the literature indicate that, consistent with this interpretation of an easier problem, participants in experiments exhibit more cooperative behavior when the regeneration rate is faster (3/3).[2] Pavitt et al. (2005) compared replenishment rates of 1.2 and 1.5 – that is, where the stock of the common resource in any period is 20% or 50% higher than what was left after the previous round of extraction, up to a known, constant maximum. This implies a 'maximum sustainable yield' optimal benchmark of about 16% of the maximum amount harvested in any period in the 1.2 treatment, and one third in the 1.5. They show that sessions with a higher replenishment rate led to higher average payoffs relative to this benchmark, as well as more equal individual harvests among participants, than sessions with a lower replenishment rate, indicating a greater ability to cooperate for successful management when the replenishment rate was higher.

In Pavitt et al. (2005), the same participants played in each period, so the intertemporal congestion generated by the replenishment rate affected overall earnings for each person. Other studies have looked at replenishment rates in 'intergenerational' contexts where the participants in each period are distinct groups. Tisserand et al. (2022) set up a one-shot request game where the resource could regenerate at a high (1.15) or low (1.05) rate, finding that while harvests were significantly higher when the regeneration rate was high, they were also lower than the socially optimal level, which led to better survival of the resource. While this represents a kind of under-adaptation to the problem, it still indicates that higher regeneration attenuates the tragedy of the commons. Fischer et al. (2004) implement an intergenerational design with an appropriation problem within each generation, varying the extent of the provision problem between fast (1.85), slow (1.25) or full replenishment. The optimal and Nash equilibrium harvest rates – the parameters of the appropriation problem – were constant across replenishment conditions, but changes in the resultant resource size induced an additional consideration of intergenerational equity. With fast regeneration, the resource stock – and consequently the aggregate profit – rises across generations even under Nash extraction, while under the slow rate the stock falls even at socially optimal levels. Thus the 'growth compensating harvest level,' corresponding to the sustainable yield, was above the profit-maximizing one in the former case, and less than the socially optimal one in the latter. The authors observe harvest rates significantly higher than the social optimum and significantly lower than the Nash level in all treatments, but closer to the social optimum when regeneration rates were higher. These results suggest a kind of ecological rationality (Todd & Gigerenzer, 2012), by which people combine heuristic responses to environmental cues with explicit (for instance) profit maximization to come to compromise choices that end up reflecting the experimental manipulations of replenishment.

3.4. Asymmetry/heterogeneity

The size and regenerative capacity of the resource, and the number of harvesters exploiting it, are arguably the most basic structural components of a CPR problem. However, there are other factors that can be important in defining the environmental context of the game, including 'technological' aspects concerning *heterogeneity in access to or benefit from individual harvest*. For example, irrigation systems constitute a major class of real-world CPRs, with water diverted from a river or other water source to individual users. In such cases, upstream users have an advantage simply by their geographical location relative to the resource. To take another kind of example, in fishing or forestry it is common for resources to be unevenly distributed, allowing people in some locations to harvest

[2]Note that this appears to contradict the result in Table 1, which indicated that a slower regeneration rate (i.e., a 'harder' problem) decreased harvest levels. However, a simple correlation of regeneration rates and extraction levels is not valid if higher growth rates increase the socially optimal extraction. Such studies therefore must compare extraction rates with the potentially varied optimal amounts.

more than others, or to benefit more from a given harvest effort. It might be expected for such heterogeneity to strain a sense of *collective* action and make management of the resource more difficult. Somewhat surprisingly, then, there appear to be at least strong qualifications as to whether this is the case. People do respond to heterogeneity in largely intuitive ways, but they also seem to accept the resulting inequalities; asymmetry has little effect on the success of CPR management.

3.4.1. Asymmetry in position: First mover position

Among the more intuitive and empirically robust patterns of behavior induced by asymmetry is the *positional effect*. This is investigated through sequential CPR designs, often built over an underlying request game. In their most basic form, sequential request games are exactly that: Request games in which players announce their harvest rates one at a time, and each receives a payoff only if the sum is less than or equal to the CPR pool. The main prediction resulting from these asymmetric protocols is that request size depends negatively on position: Participants early in the sequence exploit this advantage to harvest more. Moreover, all reviewed experiments implementing a sequential protocol of play confirm the presence of this positional effect (9/9): players in advantaged positions request a larger portion of the resource, and requests decrease monotonically as a function of the players' position in the sequence (Budescu & Au, 2002; Budescu et al., 1992, 1995a, 1995b, 1997; Janssen et al., 2011b; Pfaff et al., 2015; Rapoport et al., 1993; Suleiman et al., 1996).

The positional effect appears highly structured: It diminishes in strength over the sequence Budescu et al. (1995b), and elicited beliefs reveal that subjects anticipate it to occur. While it strongly affects the distribution of requests across the group, moreover, it has little effect on the aggregate request level (Budescu et al., 1995b). This implies that users condition their requests on information about the sequence. In particular, they appear to take into account (a) their position in the sequence, and (b) the aggregate extraction of preceding players, which has led to several extensions of the design. In the *positional protocol* (Rapoport et al., 1993) players know their position in the sequence but not the requests of the preceding players, while the *cumulative* protocol (Budescu et al., 1997) takes the inverse strategy, informing participants of the total previous requests, but not their exact position in the sequence. Evidence of the effect was found to survive all of these changes. Hence, this suggests that sequential dilemmas only require partial information, whether about position requests or previous aggregate requests, to trigger the positional effect.

Thus the positional effect appears to influence the perception of the nature of collective involved in CPR management, rather than whether or not collective action is perceived. Later movers have less 'power' in the interaction, and consequently receive lower benefits from the resource. This interpretation is bolstered by the results of designs that maintain the sequential structure, but give more power to later players. For instance, note that while asymmetric position reduces the maximum pool available for downstream players, these do still have a kind of 'punishment' option, since by overextracting themselves, they can annihilate the pool for everyone. This gives the game a feel akin to an ultimatum game. While (as in the ultimatum game) this changes nothing with respect to the subgame-perfect equilibrium strategy, Suleiman et al. (1996) find that if positions in the sequence are fixed and commonly known for a series of repeated rounds, the threat of punishment by players located at the end of sequences is sufficient to induce a more egalitarian distribution of requests.

Power can also be shifted to downstream players through participation in other components of the interaction. One of the main examples from the literature comes from irrigation games, which, in the terminology of Ostrom et al. (1994), maintain the sequential appropriation of the resource, but add a 'supply-side' provision component. More concretely, participants first receive an endowment of tokens and decide how much to invest in 'infrastructure.' This investment has a public good characteristic – indeed it is often a linear public goods subgame, and is then depleted by sequential requests. In these games, upstream users rely on the downstream not just to refrain from 'punitive' overextraction, but also to invest in the public good that generates the CPR. While they still tend to produce an unequal distribution in both the investment and harvest phases, favoring upstream users

https://doi.org/10.1017/eec.2024.6 Published online by Cambridge University Press

(Au & Ngai, 2003; Cardenas et al., 2011, 2013; Janssen et al., 2011a, 2011b, 2012; Pham et al., 2019), the effect is attenuated. Upstream users leave sufficient resources for those downstream to stimulate them to continue their contributions to the public infrastructure (Janssen et al., 2012) and are themselves more willing to contribute to the infrastructure because they are aware that they benefit more from the resource than downstream players (Cardenas et al., 2011).

3.4.2. Asymmetry in harvest limits and rewards

We can interpret the results above to suggest that participants in CPR experiments accept the power asymmetries induced by sequential requests as somehow legitimate features of the game. They influence behavior, but do not appear to have substantial impact on the ability of the group to collectively manage the resource. This effect persists in somewhat attenuated form in other designs without the structural 'justification' of sequential access. For instance, 75% (3/4) of studies that limit different participants' harvest capacity to different levels find that high-capacity participants partially exploit this to gain greater rewards, although the overall efficiency of resource use is not affected. On the other hand, both (2/2) studies that implement asymmetry through heterogeneous exchange rates of points to money or points to harvest effort find that participants tend to compensate for the differences in order to equalize outcomes.

Samuelson and Messick (1986b) found that users allowed to harvest from 0 to 30 units per round indeed extracted more than those allowed to extract from 0 to 10 units in absolute terms, although proportionally to their respective maxima the former 'high access' participants extracted much less (11.40 out of 30 units on average, compared with 7.75 out of 10). However, the high-access participants reacted significantly more than did low-access to feedback suggesting aggregate overuse of the resource, suggesting that they recognize the extra responsibility their position imposes, rather than taking it as their 'due.' Similarly, Nockur et al. (2020) find that advantaged participants, with twice the individual harvest capacity of disadvantaged, make significantly larger requests in a dynamic request game, a result again found in Holahan (2009). On the other hand, Pavitt et al. (2006) compared symmetric-limit groups in which each participant could harvest up to 25 units in a dynamic request game with asymmetric limits, in which some group members could harvest 35, 30, 20 or 15 units. They find that neither the average harvest, nor even the standard deviation within groups, differed significantly across conditions, although they note that their study was underpowered to test this hypothesis.

Heterogeneity in reward can be implemented with different money-to-point exchange rates (Budescu et al., 1990), or in the reward of points per unit harvested (Pavitt et al., 2006). This leads to a conflict between the equality and equity norms, as equal harvesting across player types (and thus equal impact on the resource) leads to unequal payoffs. Budescu et al. (1990) gave exchange rates of 0.25, 0.5, 1, 2, and 4 to the different members of an extraction group. They found that subjects attempted to compensate for the asymmetry in benefits with privileged subjects decreasing their requests and underprivileged subjects increasing theirs (which supports the equality norm). However, authors observed that asymmetric groups were equally unsuccessful as symmetric groups in tacitly coordinating the decisions of their members and having their requests granted. In Pavitt et al. (2006) members differed in their reward per unit harvested (8, 6, 4, 2 per unit). Again, average harvest rates did not differ from the symmetric condition, suggesting that the collective action was not impeded. On the contrary, in fact, the design gave participants the opportunity to develop explicit (although unenforced) rules for management, and found that asymmetric reward groups were more likely to choose to hit upon an allocation norm giving equal payoff for everyone (equality norm) than were symmetric groups.[3]

[3]As a particularly clear example of how asymmetry does *not* compromise collective action, the authors note one outlying 'brilliant' group in the asymmetric condition, which realized that group payoff was maximized by giving all harvest rights to the participant with a reward per unit of 8, who then made transfers after the experiment was over.

3.5. Manipulating (un)certainty

It is a strong, and indeed profoundly unrealistic, assumption of the basic designs discussed above that participants know the basic environmental 'facts' of the CPR with certainty. In practice, for most real CPR users, neither the exact resource size, its (possible) generation rate, nor even the number of others concurrently harvesting from it, will likely be certain. It is therefore useful scientific knowledge that experimental uncertainty regarding these aspects of the game has been found to influence individuals' decisions. This section explores the manipulation of uncertainty in three key dimensions – regeneration rate, group size, and resource size – and investigates its impact on harvest rates. We uncover an interesting pattern, where uncertainty about regeneration rate (2/2) and resource size (16/16) appears to increase harvests and make resource management harder, while uncertainty regarding group size (2/2) has the opposite effects.

3.5.1. A strange asymmetry

To begin with regeneration rate uncertainty, in Hine and Gifford (1996), the average regeneration rate was 2 (i.e., a doubling of the fish remaining in the pool), but in the unknown treatment it varied between 1.25 to 2.50. They found that regeneration rate uncertainty resulted in increased harvesting at the individual level and reduced resource management efficiency at the group level. These results were supported by the experiment of Roch and Samuelson (1997), which provided subjects with an interval for the growth rate in the resource dilemma and then compared environments with small (between 1.24 and 1.26) and large (between 1.02 and 1.48) intervals. Holding the mean growth rate constant, a larger interval of the resource's growth rate induced higher extraction levels.

A similar phenomenon arises with resource size uncertainty. Such studies represent the bulk of the literature introducing uncertainty in the environmental game attributes, and often compare pools of known size to unknown pools of high (e.g., between 100 to 900) or low (e.g., between 400 to 600) variance. All studies (16/16) have shown that uncertainty regarding the size of the resource leads to overharvesting (Botelho et al., 2014, 2015; Budescu et al., 1990, 1992, 1995a, 1995b; de Kwaadsteniet et al., 2006, 2007; Gustafsson et al., 1999, 2000; Hine & Gifford, 1996; Messick et al., 1988; Rapoport & Au, 2001; Rapoport et al., 1993; Roch & Samuelson, 1997; Suleiman et al., 1996). Participants took significantly more points from the common pool as pool-size uncertainty increased, and they tended to overestimate the actual number of points in the pool (and thus to harvest accordingly). Subjects also expected others to request more and displayed more variability in their requests as the level of resource size uncertainty increased.

Contrasting with these results, uncertainty about the group size appears to induce more cautious resource management. Au and Ngai (2003) investigated the effects of group size uncertainty in a single-choice CPR game under different protocols of play. In the group size certainty condition, participants were told that the group size was five, whereas in the group size uncertainty condition, they were told that their group was equally likely to be any size between three and seven persons. Under group size uncertainty, participants apparently acted as if the group size was large and requested less to avoid collective overuse. In a second study by de Kwaadsteniet et al. (2008), participants in the uncertainty condition were told that the number of group members would be randomly drawn from a uniform distribution of between two and eight people, whereas in the certainty condition they knew that the group size was five. They also found that group size uncertainty reduces aggregate extraction.

It has been observed that this asymmetry would be 'explained' if subjects consistently overestimate the size of the uncertain aspect of the game (Mantilla, 2018). However, the reasons behind this overestimation remain somewhat obscure. Simply positing that participants struggle with mathematics and misperceive the probability distribution (perceptual bias) appears to beg the question: why always an overestimation? And biases related to 'optimisim' or 'selfishness,' which would both potentially result in underweighting states of the world that result in low payoffs, should arguably not increase harvest under some kinds of uncertainty but decrease it under others. Finally, one might expect that a kind of 'uncertainty discounting' by which people gave less consideration to unknown aspects of the

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game would result in greater harvest rates where the group size was unknown, but lower when the resource size was unknown, which is the opposite of the observed pattern. On the other hand, recall from section 3.2 that the greater part of (the admittedly limited) research on different sized resource stocks suggested that *smaller* stocks could increase harvest rates. This would add another possibility: Uncertainty in group size or resource size is always interpreted 'pessimistically,' but, again for reasons that are not entirely clear, pessimism over the former leads to lower harvest, while pessimism over the latter leads to higher. Overall, this appears to be an area in which more research is warranted.

3.5.2. A counterexample: Probabilistic loss

Many CPRs are fragile, subject to sudden and unanticipated destruction. It is one of the more well-established behavioral phenomena that uncertainty framed as a loss generates different, and specifically more risk-averse, responses than that framed as gains (Kahneman and Tversky, 2013). Loss aversion could therefore be relevant in this context, particularly given the finding that un-framed resource uncertainty is met with behavioral 'optimism' corresponding with a kind of risk-seeking behavior.

Studies where the uncertainty in resource size is framed as a probabilistic loss, or chance of resource destruction, do indeed mitigate this effect: In 60% (3/5) of such papers, a probabilistic loss tends to have a rather positive impact on resource preservation. Blanco et al. (2017) implement a request game in which the likelihood of a shock (that destroyed 10, 50 or 90% of the value of the public good) increases with aggregate harvest rates. On average, groups became more cooperative (reduced their requests) as the likelihood of a shock increased. The phenomenon was replicated in two separate papers by Safarzynska (2017, 2018), which compare dynamic investment (rather than request) games in which the stock of a resource was subject to an exogenous (rather than behaviorally generated) shock that could diminish a fraction of resources in each period to a standard CPR with no shock treatment. Her results support the hypothesis that this uncertain danger of sudden depletion encourages resource conservation. The difference between responses to neutral and loss-framed uncertainty is therefore robust to different game forms and sources of the loss.

It does not appear to be absolute, however. Safarzynska shows that the addition of either intergroup sharing (Safarzynska, 2017, where subjects could donate some of their harvests to augment the resources of another group) or intergroup conflict (Safarzynska, 2018, where CPR groups could steal form each other) eliminated the positive impact of shocks on resource conservation. And two other studies, based on investment games with a probability of total destruction of the resource increasing with the group harvest, also show that the caution such a risk induces is not always sufficient. Walker and Gardner (1992) introduced a 'safe zone,' or harvest interval with a null probability of resource destruction, which induces a subgame perfect equilibrium outcome where the resource survives the game. This decreased the average harvest in the laboratory, but only temporarily; in most groups this equilibrium could not be sustained, and the resource was destroyed. Müller and Vickers (1996) replicated this experimental design and confirmed the results, before proceeding with an extension allowing communication between participants (see section 4.1.1). Uncertainty about losses in itself did not generate sufficient caution for the resource to be used efficiently.

4. Institutional issues

Since the pioneering work of Elinor Ostrom and colleagues (Ostrom, 1990, 1993; Ostrom et al., 1994), one of the most intriguing aspects of CPR problems has concerned the empirical observation that *real users of CPRs are often able to develop formal or informal rules enabling their sustained use*. The experimental literature has in the intervening years taken up the challenge of investigating the success of different institutional rules, in the sense of organizational structures that may be under social control. We present summaries of this literature in three parts. First, we discuss informal measures including interpersonal communication between harvesters and the provision of objective information about

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harvests. These are informal in the sense that they do not directly influence material capacities or payoffs, in distinction from the formal measures we present next, which include privatization and punishment or reward. We end with a discussion of measures that somehow combine the power of formal and informal institutions, in which the establishment or enforcement of formal rules arises endogenously as a choice of the participants.

4.1. Informal measures

4.1.1. Communication

The finding that 'cheap talk' – non-binding verbal communication between independent parties – substantially improves behavioral responses to social dilemmas is surprising, but mainly to game theorists. In the context of CPR dilemmas, the power of talking was recognized early (Ostrom, 1990), and although the strength of the effect may vary across subject pools (Cardenas, 2007; Velez et al., 2010), it remains probably the most robustly powerful single measure encouraging successful laboratory management of CPRs. Participants make active use of such preplay communication even when it is costly to do so M. Janssen et al. (2014), and in all the laboratory experiments implemented (24/24), allowing participants to communicate has been found to be beneficial for individuals and for the resource (Baerlein et al., 2015; Cardenas, 2003, 2004, 2007; Cardenas & Carpenter, 2011; Cardenas et al., 2004; De Geest et al., 2017; Del Pilar Moreno-sánchez & Maldonado, 2010; Janssen, 2013, 2010; Janssen et al., 2010, 2011b; M. Janssen et al., 2014; Messick et al., 1988; Müller & Vickers, 1996; Ostrom et al., 1992; Pavitt et al., 2005, 2006; Pham et al., 2019; Schmitt et al., 2000; Travers et al., 2011; Velez et al., 2010; Wade-Benzoni et al., 2002, 1996).

Investigation of the content of communication reveals that it operates through several channels. It allows harvesters to coordinate their actions (particularly in cases of uncertainty) and to set up aggregate extraction strategies such as individual extraction limits or informal division of the resource, and also to engage in informal sanctioning when such rules are violated. Further, it appears that even when such specific measures are lacking, communication can still have an efficiency-improving effect, suggesting a third channel involving more general trust and social distance reduction.

Its effects, moreover, have been found to be persistent over time. Janssen et al. (2010) showed, by altering periods of non-communication and communication, that communication leads to a significant increase in the payoff of individuals, and when communication is not allowed in subsequent periods, previous communication still have a positive effect on the level of cooperation. These results were replicated in Janssen (2013), in which communication was available during the first half of the rounds but not during the second half. When communication was no longer possible, on average, the resource levels did not change significantly compared to the rounds with communication. There are limits to this persistence, however. It has been shown that the increased cooperation from one-shot communication dies off relatively quickly, while repeated communication enables subjects to discuss long-term extraction strategies and maintain high cooperation rates (Cardenas et al., 2004; Ostrom et al., 1992).

4.1.2. Informational feedback

The conjecture noted in section 3.1 that large groups impede CPR management through uncertainty about strategies suggests the effectiveness of simply informing participants about the state of the resource as a institutional method. This is also interesting from a policy perspective: Central authorities may possess either better information about the aggregate harvest rate than individuals do, or scientific knowledge about the effects of individual choices that those individuals lack.

Such feedback has taken different forms in the literature, sometimes referring to the resource itself, and other times to the individual choice made by the participant. From the perspective of

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experimental methodology, it is also worth mentioning that several studies circumvent endogeneity problems in such designs – after all, the participants who overuse the resources are the same ones likely to see warning messages about overuse – through deceptive designs with pre-selected messages of 'overuse' or 'underuse' independent of actual choices.

Overall, experimental CPR users effectively use information to behave and extract the resource more efficiently: 80% (8/10) of studies found that giving feedback regarding the level of resource use reduced harvest levels and increased their efficiency. Subjects harvest less when informed that the resource is overused than when the message suggests optimal use or underuse, and harvest rates tend to increase through time in the latter two conditions but little or not at all in the overuse condition (Messick et al., 1983; Ruve & Wilke, 1984; Samuelson, 1993; Samuelson & Messick, 1986b; Samuelson et al., 1984).

However, it also appears that participants do not blindly follow the implicit recommendations in such messages, but evaluate their credibility based on other observed characteristics of the CPR: Warnings stressing an immediate crisis will be more effective than warnings that suggest a crisis may eventually develop, but the more warnings there are, the less effective they become, in a 'boy who cried wolf' effect (Joireman et al., 2009). Participants also react to perceptions of 'self-efficacy' in the sense of the expected impact of their own actions. Vasi and Macy (2003) found that people responded to crisis messages about a depleting resource by harvesting less, but only if given feedback that encouraged them to feel that their reductions in harvesting mattered. Otherwise, crisis messages may discourage participation in collective action. Martichuski and Bell (1991) crossed treatments where participants were given either positive feedback for underharvesting (such as '*good choice!*'), negative feedback for overharvesting ('*bad choice!*'), or no feedback, with a 'Golden Rule' CPR, in which a message suggested that personal action was materially valuable such as '*Here is a way to make a lot of points: When you make your choices, make them exactly the way that you would want other people to make their choices*'). They report that positive and negative feedback only worked with Golden Rule priming. Parks et al. (2017) represents the exception in this small literature, finding that warnings were in fact doing more harm than good, as people rushed to extract and harvests were larger when a warning was provided.

4.2. Formal measures: Privatization, quotas and punishment

A very early description of the tragedy of the commons – indeed the inspiration for Hardin's seminal (Hardin, 1968) work – comes from a comparison between the management of common land and newly enclosed private pastures in England in the early 1800s (Hardin, 1998). The observation, at the time unexplained, was that the agricultural yield from enclosed pastures was dramatically greater than that from the commons. Today the 'obvious' explanation is that privatization resolves the non-excludability condition that generates the CPR dilemma. In the laboratory, where (with some exceptions, e.g. Janssen, 2010; Martichuski & Bell, 1991; Messick & McClelland, 1983) resources do not have the spatial representation required for explicit 'enclosures,' an essentially equivalent division of the resource is usually implemented with harvest caps or *quotas* for each individual. In order not to assume away the problem completely, moreover, in either case the division is imperfectly enforced, implying that an important methodological consideration concerns the punishment for 'poaching' or harvests over the established limits.

Results integrating these considerations have been decidedly mixed. Two (2/6) papers found that a quota with weak enforcement (generally a 10 or 20% chance of being audited along with a rather low fine if caught extracting above the quota) leads to a decrease in individual extraction compared to the open-access regime (Cardenas, 2004; Velez & Lopez, 2013), however, four (4/6) others found that the benefit of such a quota is not sustainable (Cardenas et al., 2000, 2011; Gelcich et al., 2013; Velez et al., 2010).

An alternative, and less common, experimental design applies sanctions based not on harvest relative to the CPR itself, but relative to that of others in the group. Real-life parallels to this system may be harder to identify, but in the laboratory, it appears to function relatively well, with 100% (3/3) papers finding a positive effect on harvest efficiency. Rapoport and Au (2001) study rewards and punishments administered based on relative harvests in a one-shot request game with uncertain pool size, such that (in the former case) the lowest-request harvester received a bonus, or (in the latter) the highest request earned a punishment. In their experiment, punishment decreased the rate of request and the destruction of the resource in a request game, and punishment was more effective in reducing individual requests than was providing a bonus. Similarly, Travers et al. (2011) include treatments of (a) probabilistic punishment for any extraction and (b) a lottery in which two of the five-lowest extractors (from a group of 10) receive a bonus, showing that both measures significantly increase cooperativeness (i.e., reduce extraction) relative to a baseline without sanctions, but that the effects are substantially similar. In a slightly different line, Bell et al. (1989) investigated the trade-off between different kinds of antisocial behavior in an investment game in which participants could harvest one, two or three, tokens from a CPR, or steal tokens harvested by other players. There were overall nine treatments crossing three levels of punishment probability for overconsumption (defined as harvesting three tokens) with three levels of probability of punishment for stealing (0, 25 or 75%). They found that increasing punishment for either stealing or overconsumption did lead to a decline in that respective behavior, but led to an increase in the other behavior, which they term a compensatory effect.

Privatization of any kind raises important political questions, as was again seen, for instance, in the 'enclosure riots' that occurred in pre-industrial England (e.g., McDonagh, 2013). How are subdivisions or individual quotas to be assigned? Particularly in cases of heterogeneous access to, or benefit from, harvests (see section 3.4 for studies on such differences), the sharing rules implicit in quotas may generate a tension between norms of equity and equality. Based on empirical field observations of real CPR users, for whom heterogeneity may often be visible in harvest history, some studies using dynamic or repeated games also implement sharing rules in any given period based on previous extraction history. This question becomes particularly urgent when enforcement of the limits is imperfect, to the extent that this case relies on individuals to accept the rules established. Leibbrandt and Lynham (2018) investigated the interaction of equity and enforcement probability with three different conditions on quotas. In their inverse-proportional condition, those who had overharvested when unconstrained were allocated lower quotas; in the equal condition the resource is divided evenly, regardless of previous harvest rates; finally, a proportional condition that highlights inequity by 'rewarding' overharvesters from the first block with higher shares in the second. Crossed with this, they consider different levels of *monitoring*, with penalties for harvesting more than one's own quota imposed with zero percent (social norms), 10% (mild law, non-incentive compatible) or 50% (theoretically deterrent) probabilities. They find that unmonitored and deterrent penalties for privatization rules have more impact than do mild-law ones, and less equitable privatization schemes induce lower levels of compliance.

4.3. Endogenous regulation

A number of factors align to make endogenous formal rules for CPR maintenance – that is, formal rules adopted voluntarily by the users of the CPR – an interesting field of study. Field studies at least since Ostrom (1990) studying the successful self-management of real life CPR resources have highlighted the importance of a combination of formal and informal rules; endogenous rules in this sense appear to represent just such a combination. It was noted above, moreover, that the effect of informal measures such as direct communication appeared to pass in part through development of some structured expectations, but that exogenous measures without the informal backing were less effective. Indeed, autonomous design of management strategies is among the key 'design' principles that Ostrom (1993) distilled from empirical field studies. At a more theoretical level, endogenous regulations link to a literature on the *direct democracy effect*. According to Jacquemet et al. (2021), participative development of regulations may influence its effectiveness by increasing coordination between voters, individual commitment, or a sense of the legitimacy and fairness of the implemented decisions. Finally, endogenous formal regulations open a 'second order commons problem' of determining which regulations to enact or who will bear the costs of enforcing them.

In this subsection, we will review the results of studies on three main classes of endogenous regulations. The first two correspond broadly to the regulation systems described in section 4.2 of collectively determined privatization/quotas on the one hand and punishment or reward on the other. Another branch of the literature we consider involves assigning 'leadership' roles to some subjects.

4.3.1. Endogenous quotas

A typical endogenous quota design, the earliest example of which we found was Walker et al. (2000), has two blocks of periods of a dynamic or repeated CPR game. The first block is unregulated, while the second imposes quotas through some institutional mechanism. *Proposal mechanisms* use harvest choices in the second block as 'suggestions' for quotas: The *median harvest rule* automatically imposes the median suggestion on each group member, while the *random dictator rule* chooses one suggestion at random from the group. *Voting mechanisms* add an additional stage in the second block. Suggestions under voting rules often consist of a vector of specific harvests for each group member, and then all group members vote on the proposals, with the winner (by unanimity or majority voting) being imposed for the following period.

Although conclusions regarding the first-order problem (of behavior given different rules) can sometimes be drawn from such studies, the fact that quotas, once enacted, are generally imposed by the system makes the design particularly useful to investigate the second-order problem: A change in harvest decisions in the knowledge that those decisions may generate a rule for all group members corresponds better to choosing the appropriate rule than to choosing to follow a given rule. Moreover, while the first-order problem is generally quite well resolved (5/5 studies where such conclusions are clear), the results on the second-order problem are more mixed. Median harvest rules mechanically eliminate extremes, and under voting mechanisms participants tend to commit to sustainable harvest levels. But other factors can impede such coordination, and overall 44% (4/9) studies find weaknesses in the ability of participants to do so.

As mentioned, Walker et al. (2000) was an early study in this field, comparing unanimity and majority voting rules for vector propositions between each period of the second block of a repeated investment game, against the benchmark of a repetition of unregulated play. Any proposal voted in was implemented by the experimenter; if no proposal passed, the next period was unregulated. They found that unanimity worked slightly better than majority voting at reducing overharvesting, but that either rule raised efficiency of harvest close to 100% relative to socially optimal levels when a proposal was agreed upon; and interestingly efficiency was increased substantially even when no proposal met the required number of votes. Such results fit well with both the coordination and legitimacy aspects of the direct democracy effect.

Subsequent literature has by and large confirmed these findings, although with nuances and caveats. Bernard et al. (2013) implement a ten-period repeated investment game with groups of nine subdivided into subgroups of three. They compare an autonomy condition of independent play with conditions they call *global democracy, local democracy* and *delegation*, in which, repectively, median votes for extraction among the nine group members, three subgroup members, and exogenously determined (random) 'leaders' are imposed on all other players. They find that global democracy and delegation both significantly reduce harvest rates and increase efficiency relative to autonomy, while local democracy, even though initially effective, attenuates over time resulting in overall insignificant effects.

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The idea that endogenous regulations rely on impressions of legitimacy is consistent with the work of Vollan et al. (2013), who find in a framed field experiment that endogenous rules did not guarantee compliance if they conflicted with local ecological norms outside of the lab. Velez et al. (2012) similarly also show that CPR users can have a hard time with the second-order problem. In a framed field experiment among actual fishers in Colombia, they found that 80% of participants failed to vote in favor of theoretically deterrent enforcement levels in a repeated investment game. More postively, Silva et al. (2021) study the legitimacy effect in a repeated investment game in which participants have the opportunity to vote on quotas between the second and third of four rounds of harvest. The authors compare treatments in which the quotas are 'voluntary,' in the sense that violations are not punished, with those that are 'mandatory,' with violation generating a probabilistic sanction, and three levels of information provision. They find that after experiencing two rounds of resource decline, groups voted in favor of both kinds of quota, but significantly more so when they had more information about the pre-quota harvest levels of other players in their groups. Both kinds of quota also induced harvest rates to fall to close to efficient levels. More squarely focused on the second-order problem, Hauser et al. (2014) implement a one-shot intergenerational request game, in which distinct groups of participants make sequential requests, and can harvest the requested amount so long as the aggregate requests of all previous 'generations' did not exceed the request threshold. This design isolates the second-order problem in that resource survival does not benefit the harvesting 'present.' They also use a median-vote mechanism, noting that a large part of the resource collapse was caused by a minority of participants with very high requests. The median vote works partly through a mechanical process, since these free riders are constrained in their requests by the necessarily lower values of the median. However, the results also show some more 'psychological' effects, as the average request itself also falls in the voting condition compared to no regulation.

A particular focus in the literature has been on the effect of heterogeneous groups, which might be expected to react differently to both orders of the problem. Margreiter et al. (2005) extend the Walker et al. (2000) design with heterogeneous harvest costs in a repeated investment game with votes on proposals for harvest vectors between each period, reporting that proposals are much more likely to be accepted when harvest costs are homogeneous. On the other hand, Nockur et al. (2020) implement a dynamic request game with doubling of the remaining resource between periods, up to a given maximum. They compare individual harvest with collective average harvest rules in which either the median or mean request was implemented for all group members, crossing these conditions over an asymmetric capacity, in which two out of four harvesters had twice the individual maximum request possibilities. They report that the implemented rules significantly reduced extraction rates, particularly by reducing the extraction of the advantaged participants. Finally, Freeman and Anderson (2017) endogenize quotas somewhat differently. They allow heterogeneous participants (with differing externality costs in a repeated investment game) to spend experimental currency in a 'lobbying effort.' Participants are presented with one of a variety of preliminary caps on extraction; the final cap is adjusted by the total lobbying expenditure of the matching group. They find that participants do not manage to solve this second-order public goods problem except in cases of extremely high initial caps.

4.3.2. Peer punishment

Endogenous reward has received little attention in the literature, but several studies have looked at the effects of giving players more or less decentralized opportunity to punish each other to maintain cooperation. Perhaps surprisingly, punishment alone is often not enough to maintain a high level of cooperation; only 14% (1/7) of the studies finds substantial efficiency gains from allowing players to 'fine' each other for overextraction. There are two different reasons why this occurs. On the one hand, when punishment is costly to the punisher, it is once again an example of a second-order public good: Players do better by free-riding on the punishment efforts of others, with a resultant prediction of under-punishment and therefore non-deterrence of overextraction. On the other hand, the costs of the punishment can attenuate and even outweigh the efficiency gains from reduced extraction. A general message from the literature is that coupling punishment with communication is a better alternative.

Ostrom et al. (1992) conducted one of the first CPR experiments with peer punishment. In their study, participants could pay a fee to fine another participant. They found that significantly more sanctioning occurred than predicted and that sanctioning alone was not an efficient institution. Only when a communication treatment was coupled with a sanctioning treatment could they reduce overharvesting. Janssen et al. (2010) found similar results. In their experiment, participants used (costly) peer punishment, but without communication, it did not increase net payoffs. Cason and Gangadharan (2015) again found similar results while examining the effectiveness of costly peer punishment. Their findings confirm that peer sanctioning has a negative but limited impact on extraction, highlighting that the increase in cooperation does not generate a high enough return to compensate for the costs of punishment, which did not lead to an increase of efficiency. Kingsley (2015) confirmed again that peer punishment alone does not improve welfare in the CPR game despite increasing cooperation. De Geest et al. (2017) set up a CPR game in which a group of users, called 'insider,' could simultaneously observe and sanction (imposing a costly fine) none, all, or a subset of the second group of subjects called 'outsiders' or 'poachers.' The authors found that the insiders were not able to fully deter outsiders, mainly because the sanctions imposed on poachers were too low and insiders were unwilling to punish low levels of poaching.

Safarzynska (2020) extends Safarzynska (2018) to study costly punishment. The design features a dynamic request game with a logistic replenishment function implying an interior 'maximum sustainable yield' on harvest rates, and the characteristic that all profits are lost if the resource collapses entirely. Each period, participants can pay a 'tax' to gain the right to sanction others. Those who pay the tax can propose a maximum harvest rate; a random-dictator mechanism is used to determine which proposal is accepted. The paper compares a baseline without sanction to a 'first-order punishment' condition in which the sanction is imposed as described above, and a 'second-order punishment' condition in which if any participant pays the tax, the penalty is imposed on all participants who did not pay the tax. Results show that the second-order punishment condition greatly increases the frequency with which the taxes are paid (and hence the sanction introduced), but that the overall levels of efficiency are only weakly improved. Fewer groups completely exhausted the resource with second-order punishment, but resource levels were not significantly different.

McCusker and Carnevale (1995) implemented a 12-round investment game, comparing a baseline (no sanction) treatment with (a) rewards for the lowest extractor and (b) penalties for the highest extractor, with the total level of the sanction equal to the sum of 'sanction points' allocated by the participants in a round. They found that rewards significantly reduced extraction rates, but penalties did not result in behavior significantly different from the baseline.

4.3.3. Vote for the implementation of a central authority/leader

Another formal measure stemming largely from the psychological literature turns on the assignment of different roles to different players. While a first mover is in some ways a de facto 'leader' in the extraction game, the identification of a 'leadership' role for one player can also trigger a sense of entitlement, coordinating expectations for both leaders and followers and resulting in greater extraction by the former than the latter. De Cremer (2003) and De Cremer and Van Dijk (2005) use a deceptive experiment in which all subjects are told they are moving first, but some are also informed they are 'leaders.' Participants assigned to the leader role took more from the common resource than did participants assigned to the follower role. They also tended to violate the equal division rule more regularly than followers.

Endogenizing leadership roles turns out to be another area in which self-determined characteristics of the CPR result in better performance at the group level than do experimenter-imposed ones.

Appointed leaders took more for themselves and felt less socially responsible than elected leaders, for whom there is no difference in allocations compared to followers. Indeed, when elected as leaders, subjects were on average more moderate in harvesting from the resource than regular group members. Moreover, elected leaders tend to allocate outcomes equitably between group members, although they do not always succeed in reaching an efficient outcome (Messick et al., 1983; Ruve & Wilke, 1984). Thus, a central authority only promotes cooperation when it is democratically elected in 100% (3/3) of studies (De Cremer & Van Dijk, 2008; Gatiso & Vollan, 2017; Naquin & Kurtzberg, 2018).

However, the election of a leader entails participants giving up unrestricted access to the pool. What motivates them to do this? It has been hypothesized that leaders will only be elected if the group is perceived as being ineffective in managing the resource – ineffectiveness hypothesis – and if the outcomes are distributed unequally – inequality hypothesis – (Messick et al., 1983). Support has been found for the ineffectiveness hypothesis. When their CPR was being overused and threatened with depletion, subjects were much more willing to put a leader in charge than when their CPR was not in decline. Perhaps unsurprisingly, subjects mostly prefer to be elected as leader themselves, or prefer subjects who are similar to them, competent at the task and/or concerned for the group (Messick et al., 1983; Ruve & Wilke, 1984; Samuelson et al., 1984). However, less support has been found for the inequity hypothesis. Neither Messick et al. (1983) nor Samuelson et al. (1984) found strong evidence of the effect of inequities in the harvest on the decision to elect a leader.

5. Conclusion

In the present paper, we summarized 40 years of experimental research using CPR games. We dissected and classified this vast literature into several 'anatomical' branches of the structure of the CPR. For each branch, we then attempted to describe the results of existing studies on what that component of the experiment 'does.' In this sense, our review is a *functional anatomy*. A principal division was between 'environmental' features we called *environmental* and 'social' ones we termed *institutional* (although many papers cover interactions between the two), perhaps analogous to the skeletal and nervous systems in human anatomy. Within each system, we identified several component subsystems.

Environmental features of the CPR include harvester group size, resource size, and resource regeneration rate, but we also devoted attention to problems of heterogeneity in harvest sequence or capacity, and problems of uncertainty along one of the dimensions. Our reading uncovered an interesting nexus of results regarding group and resource size. More fishers (group size) had little effect, but fewer fish (resource size) generally caused a harvest 'rush' that reduced efficiency. But while uncertainty about group size reduced harvest rates, uncertainty about resource size increased them. There appears to be room for substantial work elucidating the mechanisms behind these patterns. Results on regeneration rates, by contrast, were much more intuitive. A higher regeneration rate in a dynamic game corresponds to a less severe CPR provision dilemma, and correspondingly better management of the experimental resource in the results. Uncertainty in this dimension led to higher harvest rates.

Another interesting collection of results found that participants adjust relatively well to asymmetry in access to experimental CPRs (through sequential requests, for instance), as well as that in benefits (through asymmetric harvest limits or payoffs per unit harvested). While asymmetry impeded the development of self-organized rules, an asymmetric environment did not overly impede efficient harvest of the resource.

Our study of the literature on institutional factors was separated into three categories. First, informal measures such as communication and informational feedback presented participants with the opportunity for self-organization, but included no explicit rules. These were largely found to be highly effective in improving CPR management, and interestingly, communication often worked through the establishment of ad hoc harvest rules. Second, and somewhat in contrast, formal measures that divided the resource into shares through enclosures or harvest caps, often with probabilistic monitoring and punishment for violations, were less effective than one might have hoped. Finally, studies of endogenous regulation, in which explicit mechanisms are established by which participants can adopt formal rules, or undertake decentralized punishment of violations, somehow connect the two previous branches. In particular, many address the 'second-order commons problem,' that involves determining what rules to establish or who bears the cost of enforcing them.

The results on this second-order problem were somewhat mixed. Many papers on voting show that participants are willing to collectively commit to harvesting strategies that control a minority of free riders, but also that this willingness is not absolute. And studies of decentralized punishment are more doubtful still, as the costs of punishment often outweigh the benefits that its control induces. Thus more work on the kind of mechanisms that might encourage second-order commons responsibility is likely warranted.

Some recommendations can be made from this literature review on how to build a CPR. First, since the year 2000, fewer papers implement an investment game. Since then, the standard CPR game appears to be a request game. Is it desirable to reach a consensus on the type of game to implement to measure (over)harvesting? On one hand, standardization of experiments would ensure ease in comparing results from studies conducted worldwide. Additionally, request games offer a clearer payoff structure compared to non-linear investment games, reducing potential participant confusion and ensuring better understanding of the instructions. On the other hand, strict experimental specifications may not always be feasible for a topic as broad as CPR harvest. Standardization could also pose a threat to replication initiatives in different settings, including other forms of CPR games. Therefore, instead of aiming for a standardized game, it may be more practical to establish guidelines for effective experimental practices, which lead to our second point. Second, the present insights must be used to calibrate a baseline game with rather low cooperation, so that new effects are rather easy to detect. For instance, if a CPR includes communication, feedback and quotas, there is a risk of limited variability, making it difficult to assess the impact of new interventions.

There are several topics have not been addressed in this review. First, the cultural variations in appropriation have been the topic of numerous articles (see e.g., Cardenas & Carpenter, 2011; Janssen et al., 2012. This abundant literature indeed suggests that whether the experiment takes place in South America, South East Asia or Africa might matter in terms of harvest rates. Second, research has uncovered an effect of individual characteristics and personality traits such as gender (Chermak & Krause, 2002; Mina et al., 2016), age (Akpalu & Martinsson, 2012; Velez et al., 2009) and social value orientation (Blanco et al., 2017; Brucks & Van Lange, 2007; Budescu et al., 1997). Third, there is conflicting evidence on the external validity of the CPR game(s). Most articles investigating this compare actual conduct from fishermen, hunters, lumberjacks in the field and in the lab. Some articles found that behavior in the lab predicted rather well behavior in the field (e.g., Carpenter & Seki, 2011; Fehr & Leibbrandt, 2011; Gelcich et al., 2013) whereas others did not (Gurven & Winking, 2008; Hill & Gurven, 2004; Torres-Guevara & Schlüter, 2016). A meta-analysis using aggregated data from different social dilemmas by Galizzi and Navarro-Martinez (2019) concludes in the same way. However, the different types of social dilemma games are pooled together (for example, CPR games are designated as public good games and there are no distinctions between request, investment and irrigation games). More large-scale international research initiatives should be dedicated to study the validity of these games in depth. Establishing the definitive impact of a variable through a literature check is almost impossible.

Confounding variables can always be suspected to interfere. To overcome this challenge, the authors' next project is to run a meta-analysis on individual data, to understand the role of each variable on harvesting in CPR games, a striving movement within economics (Abeler et al., 2019; Alm & Malézieux, 2021; Engel, 2011).

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/eec.2024.6.

Acknowledgements. We are grateful to Sacha Gaudron-Parry and Nicholas Mai for their excellent research assistance, along with Murielle Djiguemde, Cesar Mantilla, and Angela Sutan. We thank the special editors, David Budescu, Ido Erev, Tamar Kugler and Rami Zwick, along with two anonymous reviewers.

Funding statement. Financial support from ISITE-UBFC International Coach Fellowship is gratefully acknowledged.

Competing interests. The authors declare no competing interests.

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Cite this article: Malézieux, A., & Spiegelman, E. (2025). An anatomical review of the common pool resource game. *Experimental Economics*, 1–24. https://doi.org/10.1017/eec.2024.6