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RESEARCH

Appropriation behaviour predicted by environmental uncertainty, but not social uncertainty, in a common-pool resource game

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Abstract
The tragedy of the commons is a difficult problem. Overfishing, for example, is detrimental to all, but is a social dilemma for the fishers: do they overfish (maximising one's benefit) – or do they inhibit their consumption (accepting a reduced benefit)? Our study investigated factors that contribute to inhibition. Using a common-pool resource game, we recorded the consumption choices of 83 dyads (166 participants) in a multi-round game where each player decided on how many units of currency to consume from the common pool. The game had four rules: (1) the game ends if the dyad jointly consumes ≥100% of the pool, (2) the game continues if the dyad jointly consumes ≤50% of the pool (pool is then replenished), (3) the game continues if the dyad jointly consumes 51-99% ("depletion": pool is not replenished) and (4) no communication between players. Our study had a 2x2x3 factorial design: first factor (within-dyad) had two levels – pre or post-depletion – comparing consumption before/after a depletion event. The next two factors (between dyads) were "environmental uncertainty" (where players had complete or incomplete knowledge of the pool size) and "social uncertainty" (based on whether players knew each other in real life). In our results, we found no significant effects of social uncertainty, but significant effects for depletion and environmental uncertainty. While consumption decreased across all participants after resource depletion, the magnitude of this reduction differed depending on the certainty condition: the decrease was especially pronounced when the resource availability was initially uncertain. Furthermore, games lasted longer when there was certainty. In our results, we found no significant effects of social uncertainty, but significant effects for depletion and environmental uncertainty. While consumption decreased across all participants after resource depletion, the magnitude of this reduction differed depending on the certainty condition: the decrease was especially pronounced when the resource availability was initially uncertain. Furthermore, games lasted longer when there was certainty.

Keywords CPR games · Appropriation behaviour · Environmental uncertainty · Social uncertainty

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1 Introduction

When playing an economic game, uncertainty is literally a game-changer. For example, if one is unsure whether the other player will cooperate or defect, then it would be wise to play it safe and make less risky decisions. In our study, we investigated uncertainty in a common-pool resource game (CPR game, described below). The game lasted a number of rounds between the same two players. The aim of the game was to collect as many units of currency as possible from a common pool. However, players needed to jointly avoid taking too much. This was to avoid a limit that we called "resource depletion" (when that happened, both players were forced to play with a diminished common pool). Amongst our 83 dyads (participants), we introduced two kinds of uncertainty and measured how many units they consumed in each condition. Our first source of uncertainty concerned the real-life social relationship between the two players (friends; known; not known) – under the presumption that some extent of relationship history allows for more confidence in predicting the opponent's moves (e.g. a friend would be expected to play fairer than a stranger). Our second source of uncertainty concerned the environment of play itself. Specifically, we allowed one set of players (the certain group) to have complete knowledge of how many units were at play (this was useful information because the players needed to avoid going over the limit). For the other set of players (the uncertain group), we deliberately left them uninformed about the number of units. In our results, we found that social uncertainty did not have a significant effect. However, we interpret the social uncertainty result with caution, given that our measure of social relationship was based on an exceedingly simple three-point scale (a more detailed assessment may have yielded different results). For environmental uncertainty, we did find significant results: players that were uncertain reacted more strongly to resource depletion, reducing their consumption more than the players in the certain condition. Furthermore, games tended to end earlier when players were uncertain. We report our study in detail below. Before we proceed to our methodology, we provide a literature review to elucidate the wider context. Why is it important to study uncertainty as it relates to a cooperation game?

1.1 Literature review

Our biggest problem is that Earth is full. The total resource consumption of all human beings exceeds the Earth's capacity to generate resources (Tóth & Szigeti, 2016). In fact, Earth-fullness passed the 150% mark some years ago, driven mainly by a sharp increase in world consumption levels since the 1970s, particularly in affluent countries (Tóth and Szigeti 2016; Wiedmann et al. 2020). Earth-fullness is merely the largest of the countless world problems that revolve around international public goods (DellaSalla 2018; Héritier 2015; Yoder et al. 2022). When public goods are "subtractable" (taking one unit away reduces the overall amount), then that public good is called a CPR (Gardner et al., 1994; Ostrom 2002, 2008; Yoder et al., 2022): those resources which are depletable, widely accessible and for which there is competition to acquire. Overfishing is a well-known example (Ostrom 2008). Consider the story of the grouper fish (de Sadovy Mitcheson and Liu 2022): an apex predator in the fish world that is subject to severe overfishing due to its economic value (in terms of zoological classification, “groupers” are a family of related fish species). Many species of grouper are threatened with extinction, in part because groupers are larger fish with a slow rate of reproduction, and because they are relatively easy to catch (de Sadovy Mitcheson and Liu 2022). Overfishing in groupers tends to decimate their populations to the point that it causes economic hardship for the fishers, who then choose to venture further afield into new territories to maintain the level of catch they previously had (de Sadovy Mitcheson and Liu 2022). The depletion of grouper fish populations is an example of the “tragedy of the commons” (Hardin 1968; Dutta 1999): a crash of the public goods (where everybody loses).

Why don’t they simply fish less? This quote from Wilson and McCay (2019, p. 379) clarifies the fisher’s plight:

> “Overfishing means removing fish from the water at a higher rate than that which would produce the greatest overall production of fish over time. If any large group of people is allowed to fish without restrictions, the result is likely to be a decline in the productivity of the fish stock. The reason is simple: if there are no rules and one person decides to leave a fish in the water to reproduce or grow bigger, someone else could catch that fish the next day. Neither the first person as an individual, nor the common good, benefits from the first person’s restraint. The only one who benefits is the second person who catches the fish. In this situation, no one will voluntarily restrict his or her own fishing. It would be foolish”.

As described in the above scenario, to “cooperate” is to refrain from catching too many fish. To “defect” is to take (i.e. to “appropriate”) more than one’s fair share. Here, it would be useful to introduce the terms “social dilemma”, “social trap”, and “social fence”. The fisher (the “appropriator”) is facing a *social dilemma* (Komorita and Parks 1994): a choice between maximizing one’s own income for short-term gain; or limiting one’s consumption for the long-term good of all, not just oneself (also see Blanco et al., 2016). A *social trap* (Komorita and Parks 1994) describes the seemingly intractable human preference for benefiting oneself in the short term – oblivious or indifferent to benefiting the collective in the long term. In its most basic formulation (Dawes 1980), a social dilemma (social trap) has these two characteristics: (1) defecting accrues a higher payoff than cooperation (regardless of what others in society do), and (2) if all in society defect, then all accrue a lower payoff than if all cooperate (Komorita and Parks 1994; van Lange et al. 1992; Johnson 2003). The assumption that players will not cooperate is called the “zero cooperation thesis” (Ostrom 2014) and research tends to contradict the zero cooperation thesis: human players *do* indeed cooperate (based, for example, on social norms), even when it would be strictly more rational to be selfish (Ostrom 2002, 2014). A *social fence* (Komorita and Parks 1994) describes the inhibition one might feel (and should feel) in defecting. How do we compel appropriators to obey a social fence? Without some externally enforced motivation to do otherwise, it seems unlikely that an appropriator (e.g. a fisher) will choose the "cooperate" option and knowingly suffer a loss of income (see Ostrom (2002, p. 428). If everyone simply equates a social fence to "net loss", then it will result in a collective action problem (Svendsen 2022): the only way to preclude the tragedy is collective action (all or most obey the social fence; cf. Yoder et al. 2022). Without some kind of societal rules or laws to prevent overconsumption – the actor sees the benefits of defection in a bright light; whereas the benefits of cooperation are in the shadows.

Hardin's influential 1968 paper stimulated ongoing debates about how to manage the tragedy of the commons, but the debates have often been framed as involving a binary choice between free-market solutions and government solutions (Ostrom and Cox 2010; Tarko 2024). Collective action problems are most likely to run amok when there is a lack of external regulation (cf. Zaman 2017). However, centralised top-down governance has its drawbacks too (Tarko 2024; Héritier 2015; Ostrom 2014). A "Goldilocks" proposal (not too much, not too little) called "polycentric governance" was proposed by Nobel laureate Elinor Ostrom and others (Ostrom and Cox 2010; Tarko 2024): based on the idea that, because societies are complex, there should be a system of multiple units of self-governance, finding local ways to manage cooperation (see Baldwin et al. 2024, for a critical view). Polycentric governance puts the focus on local conditions and especially on the web of social relationships and social norms that have been built up around the neighbourhood of the common pool (Ostrom 2002; Ostrom 2014; Tarko 2024 cf. Zaman 2017). For example, think of the free-rider problem, which "is a type of social or coordination failure that occurs when those who benefit directly from resources, public goods, and common-pool resources do not pay for them or underpay" (Tarko, 2024, p. 158). Free-riders are easier to monitor and control when people know the identity of the free-riders (e.g., see Dunbar, 1999). On a more positive note, social relationships also allow for trust relationships and social capital to be developed (Héritier 2015; Tarko 2024; Ostrom 2014): people are more cooperative when they can confidently rely on other members of their communities. Tragedies of commons (e.g. consuming 150% of biocapacity, as mentioned earlier) are far less likely to occur if all appropriators stand to suffer equally when the resource has been depleted (e.g. when fishers no longer have fish to catch). When social interrelationships are added to the CPR game, defection may actually become more costly than cooperation if the defection causes damage to social relationships and leaves the defector with a bad reputation (Messick et al. 2016; Russell 2016, 2019; Russell et al. 2020). All human beings live within a characteristic social structure consisting of successively larger circles of social relationships (Dunbar 2020): intimates, various degrees of friendships, acquaintances and so forth. Obviously, trust will naturally vary across these layers of sociality (cf. Hardin 2003). This is the reason for our "social uncertainty" variable (described below).

Knowing that individual actors play a key role in the tragedy of the commons (Ostrom and Cox 2010), it is important to conduct research on the decision-making processes of individual actors, how they cooperate or defect, in relation to the other actors. Previous research has shown that individuals in resource dilemmas are highly influenced by social and contextual factors (Allison 1990; Messick et al. 1983, 1988; Ostrom 2002). This implies that there is some promise in the idea that we can find ways to manipulate context to encourage people to work together to prevent the tragedy of the commons. It is important to remember that social traps (Komorita and Parks 1994) are commonly observed in real life. Beyond the famous examples of the tragedy of the commons for sheep grazing (Hardin 1968) and overfishing (de Sadovy Mitcheson and Liu 2022), there are countless other examples that have been described (see Komorita and Parks 1994; Gardner et al., 1994; Dutta 1999; Ostrom 2002; Ostrom 2008; Ostrom 2014; van Lange et al. 1992; Yoder et al. 2022, etc.) – and some of these have been subject to detailed ethnographic study in the field (e.g. see Gardner et al. 1990, pp. 347-349). Laboratory studies in experimental economics are a useful way of investigating the details of decision-making in a controlled environment where the game is designed to approximate a commons dilemma (Ostrom 2002, 2008, 2014; van Lange et al. 1992; Yoder et al. 2022). In this paper, we follow from our previous work (Bonfrisco et al., 2025) in examining the influences of various factors in how players behave in a two-player CPR game. For the independent variables, we focus on "uncertainty" (cf. Dequech 2011; Azarian 2023), specifically on two kinds: (1) environmental uncertainty and (2) social uncertainty. Environmental uncertainty was manipulated by giving participants either complete or incomplete knowledge of the starting size and ongoing size of the common pool as the game progressed. We chose this variable because it reflects the inherent instability of CPRs, especially when large groups of actors are involved (Saijo et al. 2017). We chose the dyadic version of the CPR game because it was the simplest way to relate one player's behaviour to the other. Using two-player games to gain insight into larger societal patterns has considerable precedent in the literature (cf. Gardner et al. 1994). As van Lange et al. (1992) wrote: "...the various existing N-person generalizations of the two-person [game] are expected to capture the decisional structure of several real-life problems" (p. 5). The second source of uncertainty in our study, social uncertainty, was manipulated by determining to what extent players within our dyads knew each other beforehand (friends; known; not known), a rough approximation of the layers of sociality (intimates, friends, etc.) described by Dunbar (2020). Unpredictability is an inescapable part of any economic transaction (Azarian 2023), and one important way to reduce uncertainty is to build regular trading partners through repetition and familiarisation (Azarian 2023). In our procedure, we recorded the consumption choices of players in a multi-round game where each player (without consulting each other) decided on how many units of currency to consume from the common pool. Besides the rule about players not communicating during the game, there were three rules of the game. First, the game ended if "exhaustion" occurred, that is, if the dyad jointly consumed 100% or more of the available resource in a round. Second, "replenishment" occurred if the dyad consumed 50% or less of the resource pool; in this case, the pool was reset to its full starting value in the next round. Third, "depletion" occurred when total consumption in a round fell between 51% and 99% of the available resource: in this case, the pool was not replenished and the remaining resource simply carried over into the next round. The current study refers to this moment (when players first observe that the pool is no longer replenished) as the depletion point. Previous research has shown that, in the face of strategic uncertainty, individuals will often fail to coordinate their decisions, even tacitly (Budescu et al. 1990). However, this can be improved through repeated interactions (Axelrod 1981; Aflaki 2013; Hardin 2003) and the development of reputational information (Messick et al. 2016; Russell 2016, 2019; Russell et al. 2020) (an economist might characterise the development of trust relationships as an opportunity to reduce transaction costs). In relation to environmental uncertainty, it has been shown that individuals will overestimate the amount of the available resource and will, on average, take more of the resource compared to those operating under more complete information (Budescu et al. 1990). Empirical studies have shown that greater environmental uncertainty leads, on the whole, to more selfish behaviour in both one-shot and iterated games (Aflaki 2013). However, computer-based model simulations have also suggested that ambiguous information about a resource, in terms of missing or imprecise information, may lead to decreased consumption. This was modelled through uncertain probabilities pertaining to the sustainable size of the resource, and was apparent when particular attitudes to uncertainty are held among the individuals exploiting the resource and the resource is eroded gradually (Aflaki 2013). Empirical studies have likewise reported conflicting results, indicating that individuals decrease consumption as degradation increases (Blanco et al. 2016) but grab all of a remaining resource once it reaches a point of severe depletion and pending exhaustion is inevitable (Bonfrisco et al. 2025). We predicted that individuals in the uncertain condition would make higher mean consumption decisions than those in the certain condition, thereby playing a more reckless and less cautious strategy in the face of uncertainty about the maximum starting value of the resource available. Secondly, we predicted that these differences in mean consumption between conditions would disappear as the resources depleted and, consequently, players in the uncertain condition acquired more information about the value of the available resource. Further, appropriation decisions (how much to take) across groups were expected to reduce after the resource had been depleted by overuse in line with the findings of Blanco et al. (2016) noting that appropriation is inversely related to the extent of depletion of the resource base. Finally, we predicted a difference in cooperative play and coordination behaviour between games with a pair of acquaintances and those between strangers. In line with previous research findings, that social uncertainty leads to defection, we anticipated higher mean consumption in games where players did not know each other (Axelrod 1990).

2 Methods

2.1 Participants

A total of 182 participants were recruited for the current study and were students and alumni from Middlesex University, London, UK. The majority of participants were undergraduate and postgraduate psychology students, as the experiment was conducted within the Department of Psychology. Although all participants took part voluntarily, some received course credit in exchange for their participation. Data collection took place over the autumn and spring term in two academic years, between the dates of 11/11/2018 and 20/03/2020. Participants were assigned to one of the two experimental conditions – 68 individuals participated in the uncertain condition, while

114 participated in the certain condition. Further data collection was curtailed for both game conditions by the UK government introduction of coronavirus pandemic restrictions in March 2020 (Brown et al. 2021). Data from 16 participants were excluded following screening and all statistical analyses were conducted on a reduced dataset of 166 participants. Detailed demographic information and exclusion criteria are reported in the online supplementary material (See Appendix A, online supplementary material: https://osf.io/r9hup/). Participants were not paid for their participation. The study was approved by the research ethics committee in the Department of Psychology at Middlesex University (application numbers 5070/8122).

2.2 Materials

The study employed a common-pool resource (CPR) game, which aimed to simulate a decision-making scenario common in social settings where resources are shared. Participants were provided with datasheets which contained details of the round number and the quantity of resources that they consumed. Experimenters also ensured that they had their own datasheets to document participants' consumption choices, compute the amount of resources remaining in the pool and confirm the data entered by the participants. Samples of the datasheets along with information about ancillary data that were collected on several variables and questionnaire scales, are presented in Appendix A.

2.3 Design

A multilevel model design was used, including both between- and within-subjects' factors. The between-subjects factor was the different game conditions, labelled condition with two levels (certain/uncertain). Participants were recruited to participate in one specific condition (certain or uncertain) and were excluded from one of the game conditions if they had already participated in the other. In this research, we differentiated between depletion and exhaustion of the resource. We used the term depletion to refer to the first round in which total consumption exceeded 50% of the available resource, resulting in no replenishment of the pool in the following round. This moment, which was not explicitly signalled to participants, had to be inferred from changes in the pool size – specifically, the absence of replenishment in the following round – and marked the transition from the pre-depletion to the post-depletion phase. In contrast, we used the term exhaustion to refer to the final round of the game, in which the resource was fully consumed and reduced to zero. The repeated measures factor was a comparison of decisions made in the game at two different time points. The first time point was consumption up to and including the first depletion of the resource. The second was consumption at the end of the play, when the resource had been exhausted. This repeated-measures variable was labelled *depletion* (pre-depletion/post-depletion). An additional between-subjects independent variable (knows opponent) recording whether or not the participant knew and were friends with their opponent was also included in the analysis, to account for the influence of existing iterated relationships between players. Knows opponent had three levels based on social familiarity with the other player: friends/known not friends/unknown. Two outcome variables were assessed, mean consumption decisions made by participants and game duration, which captured the number of rounds a game lasted.

2.4 Procedure

Participants began the study by providing written informed consent and completing a demographic questionnaire (see Appendix A for details). Information was collected on age, sex, and whether participants knew their playing partner (knows opponent).

Following consent, participants were assigned to one of two experimental conditions (certain or uncertain). Prior to the game, participants received written instructions explaining the rules and objectives of the game. These instructions were supplemented with a verbal explanation by the experimenter to ensure clarity. Participants were informed that their goal was to maximise their cumulative consumption points while considering the sustainability of the shared resource. Participants were not allowed to communicate their intentions during the game (which is known to make a difference in cooperation; Kerr and Kaufman-Gilliland 1994). The experimental setup was designed to prevent participants from conferring with each other during the game.

The game consisted of multiple rounds, with participants making simultaneous decisions about the number of resource units they wished to consume. The resource pool, shared between the two players, was updated at the end of each round using the following update rule:

$$V_{t+1} = \begin{cases} V_t, & \text{if } \alpha + \beta \leq \frac{1}{2} V_t, \\ V_t - -(\alpha + \beta), & \text{if } \frac{1}{2} V_t < \alpha + \beta < V_t, \\ 0, & \text{if } \alpha + \beta \geq V_t. \end{cases} \tag{1}$$

Here, V_t represents the resource level at the start of round t and α and β are the consumption choices of players A and B, respectively. The three cases represent different levels of total consumption: (1) if total consumption was less than or equal to half of V_t, the resource was fully replenished; (2) if total consumption exceeded half of V_t but remained below V_t, the resource was depleted by the combined consumption; and (3) if total consumption equalled or exceeded V_t, the resource was exhausted and the game ended.

When participants' combined consumption exceeded the available resource, a proportional division rule was applied to allocate the remaining units:

$$\text{Allocation for player A} = \frac{\alpha}{\alpha + \beta} \cdot V_t, \quad \text{Allocation for player B} = \frac{\beta}{\alpha + \beta} \cdot V_t. \tag{2}$$

This allocation reflected competitive access to resources, encouraging participants to anticipate their partner's behaviour while strategizing their consumption.

In the certain condition, participants were informed that the resource pool contained exactly 100 units. In the uncertain condition, participants were told that the resource pool could contain anywhere between 80 and 120 units, creating ambiguity about the exact starting size. In reality, each game in this condition was assigned a fixed starting value of either exactly 80 units or exactly 120 units. Participants were not informed of this implementation detail and only learned the actual value of the remaining resource once it had been depleted below 50% of its starting level. This design simulated real-world scenarios where decision-makers have imprecise information about resource availability until after they have already begun consuming the resource.

Games continued until the resource pool was exhausted or for a maximum of 20 rounds, whichever occurred first. Participants were not informed of the 20-round limit to prevent backward-induction strategies, where knowledge of the game's endpoint might influence earlier consumption decisions (Aumann 1995).

At the conclusion of the game, participants were debriefed about the purpose of the study. Their cumulative scores, representing their total consumption across all rounds, were conveyed to them. Although the points had no real monetary value, the framing of the scores was intended to mimic real-world incentives, encouraging participants to engage thoughtfully in the task.

2.5 Statistical analyses

Generalized linear mixed models (GLMMs) were employed to analyse the effects of condition, knows opponent and depletion on the dependent variables: mean consumption and game duration (rounds). For mean consumption, a gamma probability distribution with a log-link function was applied because the variable was positive and continuous. For game duration, a Poisson distribution with a log-link function was used, as the variable represented discrete count data.

Seven GLMMs were fitted for each dependent variable (see Appendix B for full model formulae specification: Models M1–M7 and R1–R7), starting with an intercept-only model and progressively adding predictors. Interaction terms, such as condition × depletion phase, were included to explore whether the effects of environmental uncertainty (condition) on consumption varied across different phases of resource depletion (depletion). For rounds, interaction-only models were excluded due to the lack of significance of depletion as a predictor in preliminary tests of main effects.

Model selection was guided by Akaike's information criterion (AIC), which balances model fit and complexity (Burnham and Anderson 2004). AIC values measure information loss, with lower values indicating better models (Zeileis et al. 2008). This approach ensures that the selected models adequately represent the data while avoiding overfitting due to unnecessary predictors. Akaike weights, derived from the AICc values, were also calculated to provide the relative probability of each model being the best among the candidates. These weights are computed by first calculating the relative likelihood of each model based on its AICc difference (Δ_i) from the best model, and then normalizing these likelihoods so that the weights sum to one across all models. This approach allows for a probabilistic interpretation of model performance, complementing the rankings provided by AICc values. Additional post hoc analyses using supplementary models (Appendix B: Models S1–S8) were conducted to further explore interactions between condition and depletion phase.

The final models were specified as follows:

$$E[\text{Mean consumption}] = \exp(\beta_0 + \beta_1(\text{Condition}) + \beta_2(\text{Depletion})) \quad (3)$$

$$E[\text{Game duration}] = \exp(\gamma_0 + \gamma_1(\text{Condition})) \quad (4)$$

In these equations, *Mean consumption* is the average number of resource units consumed per round by participants. *Game duration* is the total number of rounds played until the resource was exhausted and the game ended. *Condition* is a categorical predictor distinguishing between certain (fixed 100 units) and uncertain (80 or 120 units) conditions. *Depletion* is another categorical predictor distinguishing between pre-depletion (up to first depletion of the resource) and post-depletion (after first depletion of the resource). Whereas, β_0, β_1, β_2, γ_0, γ_1 are coefficients estimating the effects of predictors on the dependent variables. Finally, ϵ, ν are error terms capturing unexplained variability.

Moreover, in order to verify the robustness of our findings and ensure that results were not driven merely by differences in starting resource values, supplementary analyses were conducted. These replaced the pooled condition variable (certain/uncertain) with an un-pooled starting value variable with three levels (80 units, 100 units, and 120 units). These analyses (detailed in Appendix D, Models M8-M13 and R8-R12) allowed to confirm whether the conceptual effect of environmental uncertainty could be attributed to the manipulated uncertainty of resource availability rather than a result of the different starting resource values assigned to the games (i.e., games with 80 units potentially lasting shorter than games with 120 units simply due to having fewer resources).

All analyses were conducted using the statistical software R, utilizing the `lme4` package for GLMM estimation and the `MuMIn` package for model selection and AIC comparison.

3 Results

3.1 Descriptive statistics

Table 1 provides descriptive statistics for the primary outcome, mean consumption and, the secondary outcome, game duration (rounds), by condition (*certain* vs. *uncertain*) and depletion (*pre-depletion* vs. *post-depletion*).

3.2 Mean consumption analysis

For the several generalized linear mixed models (GLMMs) fitted to analyse mean consumption using a gamma distribution with a log-link function (labelled M1 to M8 in the supplementary material: Appendix B), model selection using Akaike's information criterion corrected (AICc) showed Model M3 to be the best-fitting model. This model included the main effects of condition and depletion phase.

Table 1 Descriptive statistics for DVs mean consumption and rounds by IVs of condition (certain/uncertain) and depletion (pre-depletion/post-depletion)

Condition	Depletion phase	Mean consumption (SD)	Game duration (SD)	N
Certain	Pre-depletion	30.13 (14.17)	2.50 (1.73)	56
Certain	Post-depletion	9.84 (9.19)	2.62 (1.83)	51
Uncertain	Pre-depletion	39.41 (23.25)	1.78 (1.00)	27
Uncertain	Post-depletion	11.54 (8.38)	2.11 (3.05)	19

Table 2 summarises the four best-fitting models retained for comparison. The interaction term in Model M4 was not significant and did not improve model fit.

$$E[\text{Mean consumption}] = \exp(\beta_0 + \beta_1(\text{Condition}) + \beta_2(\text{Depletion})) \tag{5}$$

Model M3 returned the following parameter estimates:

The results show that participants in the uncertain condition consumed significantly more than those in the certain condition ($\beta_1 = 0.23, t = 2.16, p = 0.03$). Mean consumption decreased significantly in the post-depletion phase ($\beta_2 = -1.25, t = -20.23, p < 0.001$), indicating that resource depletion led to reduced consumption across both conditions (Table 3).

3.3 Game duration (rounds) analysis

For game duration, measured as the number of rounds before resource exhaustion, we fitted several GLMMs using a Poisson distribution with a log-link function (Table 4).

The best-fitting model was Model R2, which included condition as the only predictor:

$$E[\text{Game duration}] = \exp(\gamma_0 + \gamma_1(\text{Condition})) \tag{6}$$

It can be seen (Table 5) that games in the uncertain condition lasted significantly fewer rounds than those in the certain condition ($\gamma_1 = -0.31, z = -2.76, p = 0.006$), suggesting that environmental uncertainty led to faster resource depletion.

Table 2 Model comparison for mean consumption based on AICc values (organised by lower AICc values)

Model	Predictors	AICc	Weight
M3[a]	Condition, depletion	2280.5	0.451
M4[b]	Condition, depletion, condition × Depletion	2282.2	0.199
M6[c]	Condition × Depletion	2282.2	0.199
M5[d]	Condition, depletion, knows opponent	2282.7	0.151

[a] $E[\text{Mean consumption}] = \exp(\beta_0 + \beta_1(\text{Condition}) + \beta_2(\text{Depletion}))$
[b] $E[\text{Mean consumption}] = \exp(\beta_0 + \beta_1(\text{Condition}) + \beta_2(\text{Depletion}) + \beta_3(\text{Condition} \times \text{Depletion}))$
[c] $E[\text{Mean consumption}] = \exp(\beta_0 + \beta_1(\text{Condition} \times \text{Depletion}))$
[d] $E[\text{Mean consumption}] = \exp(\beta_0 + \beta_1(\text{Condition}) + \beta_2(\text{Depletion}) + \beta_3(\text{Knows opponent}))$

Table 3 Parameter estimates for model M3, predicting mean consumption

Parameter	Estimate (β)	SE	t-value	p value
Intercept (β_0)	3.36	0.07	50.17	< 0.001
Condition (uncertain) (β_1)	0.23	0.11	2.16	0.03*
Depletion (post) (β_2)	-1.25	0.06	-20.23	< 0.001 ***

3.4 Simple effects analysis

To further explore the effects of condition and depletion phase, we conducted simple effects analyses to evaluate differences in both mean consumption and rounds across phases and conditions.

For *Mean consumption*, in the pre-depletion phase, participants in the uncertain condition consumed significantly more resources than those in the certain condition ($\beta = 0.27, t = 3.17, p = 0.002$). However, in the post-depletion phase, there was no significant difference in consumption between the certain and uncertain conditions ($\beta = 0.16, t = 0.95, p = 0.34$). Within conditions, both the certain and uncertain conditions showed a significant decrease in resource consumption from the pre-depletion phase to the post-depletion phase (certain: $\beta = -1.12, t = -11.28, p < 0.001$; uncertain: $\beta = -1.23, t = -8.87, p < 0.001$).

For *Game duration*, in the pre-depletion phase, games in the uncertain condition lasted significantly fewer rounds than in the certain condition ($\beta = -0.34, z = -2.88, p = 0.004$). In the post-depletion phase, the difference in game duration between the conditions was smaller and marginally significant ($\beta = -0.22, z = -1.98, p = 0.048$). To summarise, the results indicate that environmental uncertainty (as manipulated through the uncertain condition) influenced resource consumption patterns and game duration more prominently during the pre-depletion phase, when information about the resource was ambiguous. In the post-depletion phase, participants adapted their behaviour in both conditions, resulting in reduced consumption and diminished differences between conditions.

Table 4 Model comparison for game duration (rounds) based on AICc values (organised by lower AICc values)

Model	Predictors	AICc	Weight
R2[a]	Condition	1231.9	0.310
R7[b]	Condition, knows opponent	1232.0	0.284
R4[c]	Condition, depletion	1232.6	0.214
R6[d]	Condition, depletion, knows opponent	1232.8	0.193

[a] $E[\text{Game duration}] = \exp(\gamma_0 + \gamma_1(\text{Condition}))$
[b] $E[\text{Game duration}] = \exp(\gamma_0 + \gamma_1(\text{Condition}) + \gamma_2(\text{Knows opponent}))$
[c] $E[\text{Game duration}] = \exp(\gamma_0 + \gamma_1(\text{Condition}) + \gamma_2(\text{Depletion}))$
[d] $E[\text{Game duration}] = \exp(\gamma_0 + \gamma_1(\text{Condition}) + \gamma_2(\text{Depletion}) + \gamma_3(\text{Knows opponent}))$

Table 5 Parameter estimates for model R2 predicting game duration (rounds)

Parameter	Estimate	SE	z-value	p value
Intercept (γ_0)	0.85	0.06	13.74	< 0.001
Condition (uncertain) (γ_1)	-0.31	0.11	-2.76	0.006**

3.5 Robustness analysis using starting value as predictor

Supplementary analyses we conducted in order to address a potential issue – the observed effects attributed to environmental uncertainty (condition) could be driven only by differences in resource size. Therefore, the robustness check involved the application of starting value (80, 100, 120 units) as a three-level categorical predictor instead of the pooled version used in the previous analyses. This approach was able to implement further investigations of the significant differences observed between the certain and uncertain condition – thus, analysing the root cause of such a significant result.

For mean consumption, six additional models (Models M8–M13) were tested. Model M8 included only the main effect of starting value:

$$E[\text{Mean consumption}] = \exp(\beta_0 + \beta_1(\text{Starting value}_{100}) + \beta_2(\text{Starting value}_{120})) \quad (7)$$

Note that in model M8 as well as in all the following ones 80-unit games serve as the reference category for starting value, and pre-depletion serves as the reference for depletion phase. Therefore, intercept terms (β_0 or γ_0) represent expected values when these reference levels apply.

Model M8 revealed no significant differences in consumption between the levels of starting value when comparing 80-unit games with 100-unit games and 120-unit games. This confirmed that actual starting value alone cannot explain the consumption differences observed between the certain and uncertain conditions, thus, supporting our decision to pool 80-unit and 120-unit games into a single uncertain condition.

Other models (e.g. Model M10) included an interaction between starting value and depletion:

$$\begin{aligned} E[\text{Mean consumption}] = \exp(&\beta_0 + \beta_1(\text{Starting value}_{100}) + \beta_2(\text{Starting value}_{120}) \\ &+ \beta_3(\text{Depletion}_{\text{Post}}) + \beta_4(\text{Starting value}_{100} \times \text{Depletion}_{\text{Post}}) \\ &+ \beta_5(\text{Starting value}_{120} \times \text{Depletion}_{\text{Post}})) \end{aligned} \quad (8)$$

While this model did show significant interaction effects, it was rank deficient (unable to estimate all coefficients reliably) and introduced complexity to the interpretation.

Simple effects analyses further clarified these results. In the pre-depletion phase, 100-unit games (certain condition) showed significantly lower consumption than 80-unit games ($\beta = -0.25$, $p = 0.03$), however, no significant difference was found between 80-unit and 120-unit games ($p = 0.82$). This pattern also matches our primary finding that uncertainty drives consumption behaviour. Finally, in the post-depletion phase, all starting value levels showed significant decreases in consumption – with no significant differences between them.

Nevertheless, despite these additional tests, our original model (Model M3 – Eq. 5), which included condition and depletion, remained the best-fitting parsimonious model based on AICc (2280.5, weight = 0.203).

For game duration, a similar pattern emerged. When starting value and depletion were included as main effects (Model R9), starting value alone was not a significant predictor:

$$E[\text{Game duration}] = \exp(\gamma_0 + \gamma_1(\text{Starting value}_{100}) + \gamma_2(\text{Starting value}_{120}) + \gamma_3(\text{Depletion}_{\text{Post}})) \tag{9}$$

Only when interaction terms were added (Model R10) did significant effects emerge:

$$E[\text{Game duration}] = \exp(\gamma_0 + \gamma_1(\text{Starting value}_{100}) + \gamma_2(\text{Starting value}_{120}) + \gamma_3(\text{Depletion}_{\text{Post}}) + \gamma_4(\text{Starting value}_{100} \times \text{Depletion}_{\text{Post}}) + \gamma_5(\text{Starting value}_{120} \times \text{Depletion}_{\text{Post}})) \tag{10}$$

This model Eq. 10 did show superior fit (AICc = 1213.3, model weight = 0.953). However, it was *rank deficient*, preventing reliable estimation of all parameters.

Simple effects analyses revealed that in the pre-depletion phase, the 100-unit games lasted significantly longer than 80-unit games (p = 0.008). Moreover, no difference was found between 80-unit and 120-unit games. This pattern again aligns with our original finding using the pooled condition variable. A notable interaction effect was that, while 80-unit games had fewer rounds post-depletion than pre-depletion (p = 0.03), 120-unit games showed the opposite pattern by lasting longer in post-depletion (p = 0.003). This makes intuitive sense as games with fewer starting units would be exhausted more quickly after depletion.

Although the interaction Model R10 Eq. 10 demonstrated superior fit in terms of AICc, its rank deficiency prevents reliable coefficient estimation and limits interpretability. Consequently, Model R2 Eq. 6 remains preferable for reporting purposes as it offers a theoretically coherent and statistically robust account of the effect of environmental uncertainty on game duration.

In conclusion, the additional analyses above confirm that starting value as a main effect does not account for the differences in consumption behaviour that we observed, justifying the original pooling of 80-unit and 120-unit games into a single uncertain condition. Moreover, while the interaction effects between starting value and depletion did emerge in more complex models, these faced estimation challenges due to rank deficiency. More importantly, the original experimental manipulation was designed to test participants' behavioural responses towards resource uncertainty, which is adequately captured by the uncertain variable (see Appendix D for more details regarding all the models used for the robustness check).

3.6 Summary of key findings

In conclusion, it was found that environmental uncertainty increases consumption. Therefore, participants consumed more resources when the availability was uncertain, particularly during the pre-depletion phase. Moreover, it was shown that resource depletion reduces consumption. Indeed, there was a significant decrease in consumption after the resource was depleted for the first time in both conditions. Finally, environmental uncertainty shortens game duration. This was demonstrated by the fact that games ended sooner (lasted fewer rounds) in the uncertain condition, indicating faster resource exhaustion. These findings highlight the impact of environmental uncertainty on resource use behaviours in common-pool resource dilemmas.

Our robustness analyses further confirmed that these effects were driven by perceived uncertainty rather than by differences in actual resource size. When testing models with starting value as a predictor, it was found that initial resource size alone could not explain the behavioural differences observed between conditions.

Detailed information on all models tested, including full parameter estimates and statistical metrics, is provided in Appendices B, C and D of the supplementary material. This includes our main models, robustness analysis models, interaction terms as well as the models incorporating social familiarity (knows opponent) as a predictor.

4 Discussion

The aim of our study was to find insights into the effects of ambiguity and depletion on consumption patterns and game dynamics in a common-pool resource (CPR) game. In our 2x2x3 factorial design, we investigated the influence of two kinds of uncertainty. The first was environmental uncertainty. This compared two groups, one which had complete knowledge of the pool and a second one, which had incomplete knowledge. The second was social uncertainty. This compared three dyads according to the closeness of the social relationship that they had with each other (friends; known; not known). Also, we compared appropriation behaviour pre-depletion and post-depletion. Our main result was the ecological uncertainty had a significant effect on appropriation, but that social uncertainty did not. We also found significant lower consumption in post-depletion compared to pre-depletion rounds – but only for environmental uncertainty. Also, games lasted longer when there was certainty. We discuss our results in more detail below.

The final model used for the investigation of mean consumption demonstrated that participants in the uncertain condition consumed significantly more resources than those in the certain condition. However, this difference disappeared in the post-depletion phase – which, in the current study, is defined as the period after the resource dropped below 50% of its starting value but before exhaustion. When this occurred, ambiguity in the uncertain condition ceased to exist and participants, in both conditions, significantly reduced their consumption. Therefore, it can be argued that this is caused by a behavioural response to resource visibility and depletion. In other words, this reduction in consumption may reflect a moral or ethical response, as players recognized the impact of their decisions on resource sustainability.

In regards to game duration, the chosen model revealed that games in the uncertain condition lasted significantly fewer rounds than those in the certain condition, both pre- and post-depletion. This may indicate that environmental uncertainty leads to faster resource exhaustion. However, it is important to note that no significant differences in game duration were found between the pre- and post-depletion phases within each condition.

On the other hand, an unexpected result was the lack of influence of social familiarity on consumption or game duration. In fact, although other studies have shown that familiarity fosters cooperation (Mullen et al. 1992; Axelrod 1981), the current results suggest that pre-existing relationships did not significantly affect behaviour when environmental factors were accounted for. There may be multiple reasons for the absence of a significant result. For example, some friendship groups may be more competitive than others. This may certainly be the case among male friendship groups. Further, our participants came from a background that was predominantly psychology focused and it is possible that this could be a factor influencing decisions, relative to those coming from other academic fields. Unfortunately, no comparison of sex differences in consumption behaviour was conducted, nor was it possible with this sample to compare the influence of the academic background of participants. Further research could explore these dynamics in greater depth as well as investigate sex differences in behaviour to shed light on this important matter.

Finally, in order to address the possibility that the significant difference discussed above could be driven by actual differences in resource size rather than perceived uncertainty, additional robustness analyses were conducted. These replaced the pooled uncertain condition with a three-level starting value variable (80, 100, 120 units). It was found that while some interaction effects between starting value and depletion emerged, the starting size of the resource did not account for the original effects of the condition variable. Most importantly, the best-fitting models, based on AIC and interpretability, for mean consumption and game duration remained the original ones based on the uncertainty manipulation. These findings reinforce the conclusion that participants responded primarily to informational ambiguity, rather than simply to the quantity of resources available at the beginning of the game.

4.1 Theoretical implications

The findings are consistent with earlier empirical research on environmental uncertainty, which indicates that in the absence of particular knowledge, ambiguity regarding resource parameters causes players to overconsume (Aflaki 2013). This contrasts with simulation results also provided by Aflaki (2013), who found that ambiguity could lead to reduced consumption under particular assumptions about uncertainty and consumers' attitudes toward it. This mismatch is most likely caused by changes in context and modelling assumptions. The simulations used in Aflaki (2013) adopt a more broad deterioration model that represented progressive resource erosion, whereas the current study used games with smaller resource bases (80, 100, or 120 units), with values that were easy for participants to understand and depleted quickly.

The usage of a step function in the payout structure, as implemented in the current study, has already been used in previous research (Suleiman and Rapoport 1992) and was a practical decision for the game's design. Nonetheless, future research should also look into payoff structures that incorporate gradual depletion in order to see if the current behavioural tendencies found remain the same. For instance, games with greater starting values (e.g., V = 10,000 units) may result in a more gradual depletion of the resource base. Such an approach may also show preference inconsistencies, as individuals frequently reason differently when faced with greater or smaller magnitudes, as highlighted in decision theory literature (Peterson 2009).

Blanco et al. (2016) hypothesised that resource degradation causes individuals to minimise appropriation. Consistent with this, we saw considerable reductions in consumption after depletion under both settings. However, our study only recorded the transition between two phases of the game. A more extensive examination of individual rounds would establish whether consumption decreases gradually with each depletion, as suggested by Blanco et al. Variability is probable, with some persons increasing their consumption and others decreasing it after each depletion. Nonetheless, as depletion advances, participants are likely to reach a critical level where they exhaust the remaining resource, as demonstrated in prior research (Bonfrisco et al. 2025).

4.2 Practical implications and future directions

The results demonstrate how crucial environmental uncertainty can be in influencing how resources are appropriated. The implementation of strategies to reduce ambiguity, including the provision of more transparent resource indicators or real-time monitoring systems, should be taken into consideration by policymakers and resource managers. Furthermore, the findings raise some doubts about common beliefs regarding the contribution of social familiarity to cooperative behaviour, indicating the need for more thorough research on social dynamics in CPR dilemmas.

An alternative design worth considering in future research is the use of a constant resource base of 100 units even in the uncertain condition, similar to the certain condition. In other words, participants would be only led to believe the resource ranges between 80 and 120 units, while the actual resource value is 100. This design might keep the perception of uncertainty without bringing actual diversity into the resource pool, allowing for a direct comparison of perceived and actual ambiguity. It is feasible that such a modification would accentuate or reduce the behavioural effects reported here, providing new information about how perceived versus genuine uncertainty drives resource usage.

Further studies may also attempt to investigate other scenarios to gain more insights. For instance, researchers could try to maintain the ambiguity even after the initial depletion (i.e. keeping participants uncertain even after depletion by not revealing the value of the remaining resource) in order to assess the formation of any pattern over time. Moreover, as mentioned earlier, further insights may be gained by looking at how group dynamics and sex differences influence resource appropriation, especially in cooperative versus competitive contexts. Examining models of progressive erosion may also help determine whether ambiguity affects behaviour differently in situations with slower rates of depletion or bigger resource bases.

Thinking of the broader, world-wide picture, our study is just one small piece of the puzzle. As mentioned in the introduction, the earth is consumed in resource dilemmas that have caused "Earth-fullness" (Tóth and Szigeti 2016) and our aim should be to avoid the "degradation externalities" (Blanco et al., p. 137) that represent a tricky-to-govern tragedy of the commons for the entire planet (Johnson 2003; DellaSalla 2018; Ostrom and Cox 2010; Héritier 2015; Yoder et al. 2022; Baldos et al. 2023). Experimental economics allows us to examine decision making on a microeconomic level, applicable to problems of Earth's environment even though most of the relevant published studies do not even mention the environment to its participants (Lange 2023). Although the laboratory setting might be subject to criticism for its artificiality, there is good reason to believe that experimental games are "real" in the sense of generating real decisions on the part of the players – decisions which simulate real-world behaviour in a meaningful and veridical way (for relevant discussion about this, see Dawes, 1980; Ostrom, 2008, van Lange et al., 1992, etc.). There are many reasons why individuals may choose to cooperate in games (e.g. see Allison 1990; van Lange et al. 1992, pp. 18–24; Ostrom 2002; Ostrom 2014), but it is important to remember the behaviour of the individual actor is just one small part of the whole dilemma (see Ostrom and Cox 2010, for a delineation how to analyse the "social-ecological systems" where resources dilemmas happen; see Yoder et al. 2022, on the different categories of commons that exist). The individual actor often cannot see the whole picture. As an analogy, think of the flocks of birds that fly in the sky in their tens, hundreds, or thousands, moving as beautiful undulating shapes in the sky, aggregations of black dots that appear to move as a single coordinated unit. In reality, none of the individual birds perceive the overall shape of their flock (Couzin and Krause 2003): each bird is simply following the movements of their neighbours. Like the birds, humans are overwhelmingly influenced by local conditions and solutions to social traps often seem better as a bottom-up rather than a top-down process (Tarko 2024). It is important to examine the individual motivations of the actors (Yoder et al. 2022). As Ostrom (2014) wrote: "...norms seem to have a certain staying power in encouraging a growth of the desire to cooperate over time, while cooperation enforced by externally imposed rules can disappear very quickly" (p. 242).

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Declarations

Competing interests The authors declare no competing interests.

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