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Threshold ambiguity and sustainable resource management: A lab experiment

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ABSTRACT

Overexploitation of ecosystems can cause drastic shifts to unfavourable states once ecosystems reach critical thresholds. Experimental studies have shown that the knowledge of such thresholds helps to foster sustainable resource management. However, warning resource users of a regime shift is difficult since knowledge about critical thresholds is often associated with considerable ambiguity. We conducted a continuous-time common pool resource lab experiment (N = 360; 90 groups of four participants) to assess how different levels of ambiguous information regarding the location of thresholds affect cooperation amongst resource users. Results show that groups informed only of the threshold's existence cooperate similarly to those provided with a range for the threshold, indicating that ambiguity levels do not significantly influence cooperation amongst resource users for sustaining resources at optimal levels. In addition, we analysed treatment differences once the ambiguity about the threshold location is resolved. We do not find lasting impacts of different ambiguity levels on the likelihood of avoiding crossing the threshold once the threshold location is communicated with certainty. Overall, our results suggest that the scope of providing imprecise threshold information which reduces the level of ambiguity may be limited in fostering more sustainable natural resource management.

1. Introduction

Overexploitation of resources can change the underlying conditions of ecosystems. Consequently, ecosystems can abruptly switch to an alternative state once they are driven to a critical threshold, which is referred to as a regime shift (Scheffer et al., 2001). Regime shifts often have drastic negative impacts on economies and societies (Biggs et al., 2009). Examples include the desertification of woodlands and the collapse of fisheries (Millennium Ecosystem Assessment, 2005). Prior experimental research has found that the knowledge of such thresholds can help resource users to successfully coordinate to avoid the regime shift and thus overcome the "tragedy of the commons" that refers to the overexploitation of a common pool resource (CPR) (Lindahl et al., 2016; Ntuli et al., 2023; Rocha et al., 2020). Similar results have been reported by experiments focusing on cooperation for the provisioning of public goods (Barrett and Dannenberg, 2014a). A threshold can thereby help transform a cooperation into a coordination problem, with a mutually preferred equilibrium of not crossing the threshold (Barrett and Dannenberg, 2012). Communicating critical thresholds is consequently seen as a valuable tool to support sustainable resource management (Maas et al., 2017; Schill and Rocha, 2023).

However, resource users typically face high levels of uncertainty regarding the location of the threshold and the impact of crossing it. Over time, improved data as well as scientific advances in modelling ecosystem dynamics can provide more precise threshold estimates. One example is the deforestation of the Amazon rainforest, which is predicted to cause a regime shift from rainforest to savannah, reducing rainfall and increasing temperatures in the area (Lovejoy and Nobre, 2019). Some initial signals that the Amazonian regions are approaching a critical threshold have already been observed (Lovejoy and Nobre, 2019), and estimates of the critical deforestation threshold for the Amazonia range from 20% to 40% deforestation (Lenton et al., 2019). Based on existing evidence summarized further below, resource users may be expected to be more likely to avoid crossing thresholds and causing a resource collapse, if uncertainty regarding the threshold location is reduced. However, providing vague information about thresholds may also backfire. In CPR management, resource dynamics are typically non-linear and over time resource users may learn what resource stock allows to maximize yields and consequently income over the long-term. Such levels of maximum sustainable yield (MSY) may

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provide a focal point for groups and facilitate cooperation. Communicating relatively vague threshold information may shift resource users' focal point to this lower level[1] and thereby increase resource extraction. Even if at a later stage more precise information about the threshold becomes available, path dependency of decision making may limit the positive impact of this information. Prior interactions with other resource users may have solidified beliefs about their actions and interpersonal trust, as well as affected the current state of the resource and distance to the critical threshold. In this paper, we investigate two related research questions: a) whether imprecise information about the location of the threshold affects resource users' behaviour compared to a scenario with full ambiguity, and b) whether the precision of prior information (i.e. ambiguity) affects how resource user react when the uncertainty regarding the threshold location is fully resolved.

Before summarizing the existing, related literature, it is important to introduce a few key concepts and definitions. First, we consider 'uncertainty about the threshold location' as an overarching term that refers to a situation where the exact location of the threshold is unknown to resource users, while the existence of a threshold and the impacts of crossing a threshold are known. This uncertainty can be operationalized as either risk or ambiguity. We follow Dannenberg et al. (2015) delineation that under *risk*, decision makers know the 'probability distribution over a range of possible thresholds', whereas under *ambiguity* they do not know the underlying distribution. Thus, ambiguity can be considered as a higher level of uncertainty than risk (Aflaki, 2013; Ahsanuzzaman et al., 2022). Second, CPRs with a critical threshold allow focusing on two distinct behavioural outcomes that correspond to two distinct game theoretical concepts. On the one hand, groups face a *cooperation* problem that is to sustain the resource at the MSY. At this level, groups maximize their joint income in the long run, whereas self-interested individuals face the incentive to overexploit and free-ride on the conservation efforts of others. Cooperation comes hence at a private cost resulting in a unique Nash equilibrium of non-cooperation (Barrett and Dannenberg, 2012). On the other hand, groups face a *coordination* problem to avoid crossing the threshold. Here, group and individual interests align, as nature itself acts as a sanctioning institution and averting the resource to collapse is in everyone's interest. Unlike cooperation, coordination is a Nash equilibrium (Barrett and Dannenberg, 2012). If individuals, however, expect that the threshold is crossed, it remains optimal for them to maximize extraction. In other words, both coordination and non-coordination are possible equilibria.

The existence of thresholds can have counterintuitively positive implications for sustainable management of CPRs as illustrated by Lindahl et al. (2016) who found that the existence of a threshold increases cooperation relative to a scenario without a threshold, resulting in less overexploitation and higher efficiency. Similar results have been reported from lab-in-the-field experiments with Colombian fishers (Rocha et al., 2020) and villagers managing common-pool wildlife in Zimbabwe (Ntuli et al., 2023), but not with fishers in Thailand (Lindahl and Jarungrattanapong, 2023).

But as mentioned above, thresholds in ecosystems are difficult to locate and consequently associated with uncertainty regarding various parameters. A few experiments focused on *uncertainty regarding the existence of a threshold*. Their results suggest that such uncertainty has only small to no effects on CPR management. Schill et al. (2015) find that different risk levels concerning threshold existence do not affect coordination likelihood (avoiding crossing the threshold). Schill and Rocha (2023), do not find that risk or ambiguity whether a threshold exists affects coordination likelihood (averting the resource collapse) relative to threshold certainty. To our knowledge, only two threshold public goods (TPG) experiment have analysed how *uncertainties regarding the impact* of crossing a threshold affect coordination. Framed in the context of climate change mitigation, Milinski et al. (2008) vary the risk level whether crossing the threshold has any impact on individuals. They find that a high risk of income loss after threshold crossing increases the likelihood of groups to avoid catastrophe. Barrett and Dannenberg (2012) conducted a similar experiment framed in the context of climate change mitigation and found that uncertainty about the impact of crossing a threshold had no significant effect on contributions. In their design, the minimum impact of crossing was in any case non-zero.

More research has focused on one dimension of environmental uncertainty, that is the *uncertainty regarding the location of the threshold* in the context of CPR management, which is also the focus of this study. However, this literature has predominantly compared scenarios with certainty and uncertainty about the location of the threshold or compared scenarios with different levels of uncertainty about the location. The overarching result is that higher uncertainty about the location of the threshold decreases the likelihood that groups coordinate successfully on sustainable resource management strategies. Uncertainty in the form of risk (with knowledge of the threshold's probability distribution) reduces the likelihood that groups of resource users coordinate to avert a regime shift and that resource users cooperate in order to maximize group earnings *relative to a certain threshold location* (Ahsanuzzaman et al., 2022; Maas et al., 2017). At the same time, *higher levels of risks about the location of the threshold*[2] have been found to not affect resource extraction levels (Maas et al., 2017). Similarly, studies focusing on uncertainty about the resource size conclude that the higher the uncertainty, the lower the coordination (Botelho et al., 2014; Budescu et al., 1992; Budescu et al., 1990; Gustafsson et al., 2000; Gustafsson et al., 1999; Kidwai and de Oliveira, 2020). Resource size can be considered conceptually similar to a threshold, as in both cases when extraction exceeds the size or the threshold, the CPR is destroyed and generates no further earnings.

Similar results have been reported by TPG experiments where individuals also face a social dilemma, in which self- and group-interests do not align. But TPG experiments feature several key differences compared to CPR experiments. CPR experiments usually have a take instead of a give framing, and rivalry regarding the resources exists (Apesteguia and Maier-Rigaud, 2006; Isaksen et al., 2019). Furthermore, many dynamic CPR experiments also have an interior social optimum (MSY level), e.g. due to a logistic growth model, whereas most public good (PG) experiments are linear and have a corner solution as social optimum (van Soest et al., 2016). Hence, one needs to be cautious when extrapolating PG experiment findings to CPR experiments. A series of experiments on climate change mitigation have found that uncertainty regarding the location of the threshold reduces the likelihood that groups successfully coordinate and maximize group earnings *relative to a certain location of the threshold* (Barrett and Dannenberg, 2014a, 2014b; Barrett and Dannenberg, 2012; Brown and Kroll, 2017; Dannenberg et al., 2015). Unlike CPR experiments, *higher levels of risk about the location of the threshold* have been found to lead to lower cooperation and coordination (Barrett and Dannenberg, 2014b; Gustafsson et al., 2000).

[1] Our assumption that the critical threshold of a resource that leads to a permanent collapse once it is crossed is below the MSY level is based on the theory of critical transitions in ecosystems caused by reaching a threshold (e.g. Scheffer et al., 2009; Scheffer and Carpenter, 2003; Scheffer et al., 2001). In our experiment, we focus on the case where a shift to an alternative state implies negative consequences for the resource (e.g. loss of the resource). A prominent example taken from the literature is the shift from clear water to a turbid state in a lake due to over-eutrophication (e.g. Scheffer et al., 2001; Scheffer and Carpenter, 2003). Such a negative regime shift can stress the fish population and thus can cause the loss of the resource. We assume that the threshold of the CPR cannot be above the MSY, since a negative regime shift results in a collapse of the resource and lower yields for resource users in the long run.

[2] Maas et al. (2017) vary the range of the possible threshold location (maximum and minimum) between treatments, while holding the expected threshold location constant. A larger range is thus associated with higher level of risk.

While these studies allow drawing general conclusions about the impact of threshold uncertainty, resource users often have to make decisions facing even higher levels of uncertainty. That is, rather than risk, they face *ambiguity* (not knowing underlying probability distributions). Thus far, only a few studies have analysed how resource users respond *to ambiguous threshold location knowledge.* Hine and Gifford (1996) compared in a continuous-time CPR experiment the effect of ambiguity regarding the resource size and the resource replenishment rate relative to certainty. Both types of ambiguity led to higher extraction rates and coordination failure. Ahsanuzzaman et al. (2022) compared behaviour under certain, risky, and ambiguous threshold location knowledge. Both threshold risk and ambiguity led to higher resource extraction than threshold certainty. While resource extraction is higher under risk than ambiguity, the likelihood of a resource collapse does not differ between these two scenarios. Dannenberg et al. (2015) report similar results from a TPG experiment. Both risk and ambiguity led to lower cooperation relative to threshold location certainty, but cooperation under risk and ambiguity were not significantly different. Overall, these results suggest that ambiguity about the location of thresholds hampers cooperation (and sustainable CPR management) compared to having certain threshold knowledge. However, there seems to be only minor differences in outcomes between scenarios with threshold location ambiguity and risk.

To date, empirical studies have not yet explored to what extent *different levels of ambiguity* impact CPR management. This is highly relevant since threshold knowledge often remains ambiguous even with gradual scientific advancements.

Given the dearth of studies on the impact of threshold ambiguity on CPR management, we first analyse whether higher levels of ambiguity affect the likelihood of groups to successfully cooperate and maintain the resource at the MSY level. Drawing on the empirical findings that higher levels of threshold location risk lead to more resource extraction, less cooperation and coordination, one would also expect higher levels of threshold ambiguity to hamper cooperation. Providing imprecise threshold information that reduces ambiguity may therefore provide an effective tool to foster sustainable resource management. Theoretical work, however, suggests that risk and ambiguity may result in fundamentally different conservation outcomes. Higher levels of ambiguity about the threshold could motivate coordination on a cautious extraction strategy because resource users might be more aware that experimenting with high extraction incorporates the risk of reaching the critical threshold (Aflaki, 2013; Diekert, 2017). The results of Ahsanuzzaman et al. (2022) – who compare resource extraction behaviour under risk and ambiguity – indeed find support for such mechanism leading to lower extraction rates under ambiguity than risk. Moreover, CPRs typically have a resource level of the MSY that is above the critical threshold (e.g. Scheffer et al., 2001). If resource users are aware of the MSY level, it may act as a focal point on which resource users coordinate. Then, providing imprecise information about a threshold and thus, reducing the level of ambiguity, may shift the focal point below the MSY and result in higher extraction rates.

Second, we assess whether prior levels of ambiguity about the location of the threshold also affect behaviour once the uncertainty about threshold location has been resolved. That is, we examine coordination and cooperation when the threshold location becomes known with certainty, and assess whether the results are impacted by the previous level of ambiguity. Dynamics that shift the focal point below the MSY, as outlined above, may result in different path dependencies of resource extraction. The response to more precise threshold information later on could thus be different depending on prior knowledge and resource extraction dynamics. We are not aware of any experimental study focusing on the question of whether the impact of precise threshold information is contingent on the earlier level of ambiguity. Existing experimental studies have focused on comparing different levels of uncertainty about the threshold across treatment conditions and have not modelled a gradual increase in the precision of the threshold information.

To address the lack of empirical evidence on this topic, we designed a novel (quasi-) continuous-time common pool resource (CPR) experiment for the lab to analyse if the level of ambiguity about threshold location affects cooperation and coordination amongst resource users. We compare behaviour under two starting levels of ambiguity. Under the high ambiguity level, resource users only know about the presence of a threshold and have no information about its location.[3] Under the low ambiguity level, they know the range of possible threshold locations that are below the MSY level, but still do not know the probability distribution within this range. Further, we assess whether these different levels of threshold ambiguity have a lasting effect on resource use once the uncertainty about the threshold location is resolved. We implement this by revealing the exact location of the threshold at a given time during the experiment.

We find that reduced ambiguity regarding the threshold location does not influence cooperation compared to a scenario with higher ambiguity. Furthermore, we do not find evidence that prior levels of ambiguity affect resource extraction after resource users get to know the threshold with certainty. Groups are similarly likely to cooperate (sustain the resource at the MSY) and coordinate (avoid crossing the threshold). Thus, our results suggest that the scope of providing imprecise threshold information that reduces the level of ambiguity may be limited in fostering more sustainable natural resource management.

Our paper also contributes to a broader strain of experimental literature, incorporating more complex ecological dynamics into economic experiments. While experiments have generated valuable insights for CPR management for more than two decades (Cardenas, 2000; Janssen et al., 2010; Ostrom, 2006), only recently more complex ecological dynamics have been incorporated into experimental designs (Brandt et al., 2017; Cerutti and Schlüter, 2019; Janssen, 2010). To our knowledge, we report one of the first continuous-time experiments where resource users face more complex ecological dynamics (i.e. a threshold) and uncertainty about it (except Hine and Gifford, 1996). In contrast to round-based CPR experiments, the continuous-time design allows for a more dynamic, immediate, and asynchronous interaction of resource users with the resource and each other (Pettit et al., 2014). This allows for adjustment dynamics that mimic long-term interactions amongst subjects in a relatively short time compared to conventional round-based designs. Continuous-time designs have been found to lead to higher cooperation rates than discrete-time CPR experiments, possibly because "continuous time allows for rapid and adaptive strategic choices" (Djiguemde et al., 2022, p. 1009). Therefore, groups may be better equipped to deal with environmental uncertainty under continuous time, leading to drastically different results than with the commonly used discrete-time experiments.

2. Material and methods

2.1. Experimental design

In our experiment, a group of four participants $n = 4$ jointly managed a common pool resource (CPR). Participants did not communicate at any point during the experiment. In contrast to conventional CPR experiments, we implemented a (quasi) continuous-time experiment, where the resource stock and resource users' extraction and pay-offs were updated by the second (Bigoni et al., 2015). The experiment consisted of two test rounds (90 s each) and one experimental round of at least 240 s that was pay-off relevant (see below for more information on the round length). Participants decided on an initial extraction level E_{it} between 0 and 10 at the beginning of the experimental round ($t = 1$) and could

[3] Technically, resource users also know a range for the threshold location determined by the carrying capacity of the resource as a maximum and zero as a minimum.

decide to adjust their extraction level any time during this round. The maximum frequency of adjustments was limited by the time participants required to change their extraction level. Making a change in extraction involved moving the slider on the screen to their desired extraction level and confirming the setting of the slider. This process typically took between one to two seconds. Participants' extraction was cost-free, and the amount of extracted resource units was constant per level of extraction: each unit of extraction level resulted in one extracted resource unit, independent of the current resource level. The group's cumulative extraction per second was hence $\sum_{i=1}^{n} E_{it}$. Individual extraction decisions were made anonymously, but participants were shown the development of the resource stock, the development of their personal resource extraction, as well as the cumulative individual and group sum of extracted resource units updated by the second.

As in most dynamic CPR experiments, the regrowth of the resource in our experiment depended on the resource stock (Lindahl et al., 2016; Schill et al., 2015). Eq. (1) below shows how the resource R_t changed over time t (in seconds). If the resource was above the critical threshold ($R_t > R_{min}$), the resource's natural growth was based on a logistic growth model with the growth rate $g = 0.04$ (Brandt et al., 2017; Perman, 2011). The resource development started at the resource's maximum carrying capacity (MCC) $R_{max} = 2,000$ units. If the resource was at its MCC, the regrowth was zero. Below the MCC, the regrowth per second increased until the resource reached the MSY at a resource level of 1000 units (regrowth of 20 units per second). Below the MSY, the regrowth per second decreased again. Once the resource reached a critical threshold $R_{min} = 400$ units, it irreversibly collapsed ($R_{t+1} = 0$ *if* $R_t \le R_{min}$). At this point, the resource's regrowth dropped to zero (see Fig. 1). (See Table 1.)

Hence, the size of the resource R at $t+1$ was:

$$R_{t+1} = \begin{cases} R_t + gR_t\left(1 - \frac{R_t}{R_{max}}\right) - \sum_{i=1}^{n} E_{it} & \text{if } R_t > R_{min} \\ 0 & \text{if } R_t \le R_{min} \end{cases} \quad (1)$$

where $\sum_{i=1}^{n} E_{it}$ denotes the group's joint extraction with $n = 4$ resource users per second t.

To familiarize participants with the resource dynamics, they were informed about the starting level of the resource, the MCC, and the MSY. A table in the instructions also illustrated regrowth rates for exemplary resource stocks in 200-unit steps. In addition, participants played two test rounds of 90 s each, with three other participants with whom they were not matched in the actual, pay-off relevant round. Participants were aware that these two test rounds were not pay-off relevant.

Table 1
Summary of experimental design and treatments, RU stands for resource units.

	Low Ambiguity	High Ambiguity
Group Size	4	
Decision Space	Extraction between 0 and 10 RU per second in integer steps	
Resource Dynamics	Logistic growth function, with MSY at 1000 RU, maximum carrying capacity at 2000 RU, and critical threshold at 400 RU	
Communication	Not allowed	
Length	240 s plus random continuation rule (10 additional seconds with $p = 0.9$)	
Break	At t = 58 s, exact location of the threshold (400 RU) was communicated	
Information about threshold at t = 0	Threshold located between 200 and 700 RU	Threshold exists, but location unknown

Resource users' payout P was determined in points during the experiment (1 extracted resource unit = 1 point) and was later converted into Euro with an exchange rate of 100 points = 1.00 Euro. The payout P (in points) for participant i was determined by the sum of resource units that i extracted over time t, with t_{end} seconds denoting the last second of the experiment:

$$P_i = \sum_{t=0}^{t_{end}} E_{it} \quad (2)$$

The experiment represents a social dilemma, where selfish and myopic individuals have the incentive to maximize their income by free riding and choosing the maximum individual extraction. In contrast, the social optimum differs from this. Resource users face an infinite time horizon regarding their resource extraction in real life. It is then socially optimal for the group of resource users to keep the resource at its MSY because it maximizes the group's outcome over time. However, inducing the socially optimal group extraction strategy in the lab is difficult because participants know the experiment will eventually end. As a result, cooperation typically decreases towards the end of experiments, known as the endgame effect (Andreoni, 1988). We implemented two strategies to reduce such endgame effects in our experiment. Firstly, we implemented a random continuation rule to induce an infinite time horizon in the lab (Dal Bó and Fréchette, 2018). Beyond a minimum length of 240 s, the experiment continued for another ten seconds with a

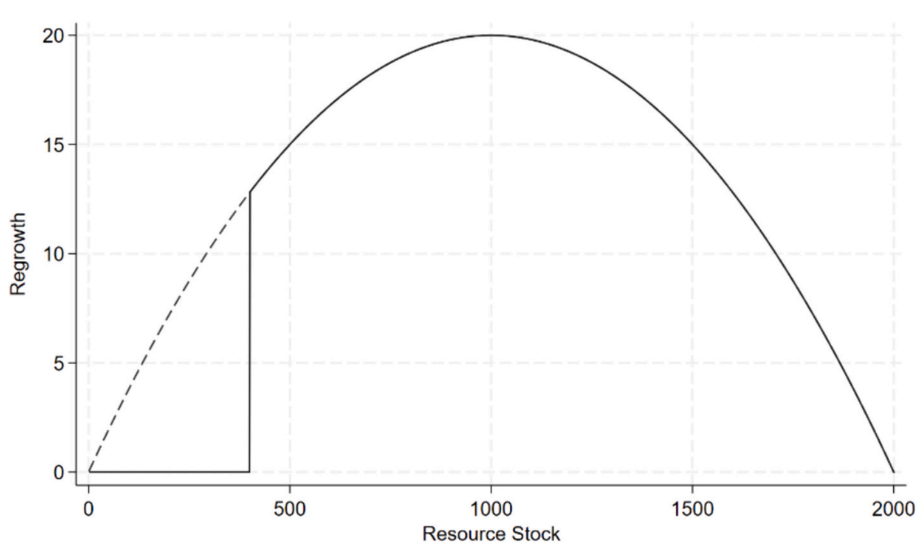

Fig. 1. Resource regrowth function in relation to the resource stock. The dashed line indicates the regrowth function without a threshold that participants faced in the two test rounds and that was used to familiarize respondents with the underlying regrowth function. Depending on the treatment, participants received more or less ambiguous information about the threshold location prior to the beginning of the pay-off relevant round.

probability of 90% in both treatments. With a 10% probability, the experiment ended. The random continuation rule was executed every ten seconds, and as long as the experiment continued, participants could collect points for their payout. Secondly, we defined 210 s as the "end" of the experiment for our analysis to avoid any influence from potential endgame effects on our results (see Supplementary Information (SI), Section A, for more details on the experimental design and optimal extraction strategies).

2.2. Treatments

As explained above, both treatments incorporated the threat of crossing a critical threshold, but they differed in participants' knowledge about the threshold at the beginning. Participants in treatment "High ambiguity" (HA) only knew that there was a threshold, without any information on the resource level at which the regime shift would occur. In contrast, participants in treatment "Low ambiguity" (LA) received imprecise information about the range of possible levels of the thresholds (700 to 200 resource units). The underlying probability distribution within this range was unknown to participants in both treatments. Thus, participants in both treatments faced threshold ambiguity.

The experiment included a pause at 58 s in both treatments, dividing the experiment into a pre- and post-pause part. During this unannounced pause, participants received the information that the threshold was with certainty at 400 units. Initially, it was unknown to participants that the certain threshold would be revealed during the experiment. The pause's timing at 58 s was late enough to drive the resource below MSY, but still early enough to prevent groups from reaching the threshold (see SI, Section A for details of the parameterization). If a group extracted the maximum until the break at $t = 58$ s, the resource would have been at 600 resource units and thus, below the known upper limit of the threshold range in LA. But since participant groups were unable to cross the threshold before the break, we only observe measures of cooperation but not coordination before the break, whereas both can be measured afterwards.

The introduction of this unannounced pause, during which the precise location of the threshold was revealed, recreates a scenario in resource management, where scientific advancements ultimately result in a significant reduction of environmental uncertainty. In reality, resource users cannot count on such information to be revealed in the future, so we considered the prior announcement of this information break as unrealistic. Nonetheless, we are aware that the information break is a simplification, as in most cases the exact location of the threshold cannot be identified with certainty. We do not consider this information omission to qualify as deception as no misinformation was provided to participants at any point of the experiment (Charness et al., 2022).

2.3. Hypotheses

For our hypotheses, we distinguish between two outcomes for sustainable resource management at the group level: (1) overexploitation below the MSY as a proxy for the failure of *cooperation* amongst group members, and (2) the collapse of the resource as an indicator of failed *coordination* amongst group members. We consider the analysis of group outcomes as more appropriate than focusing on individual extraction behaviour for two reasons. First, the time-continuous design of the experiment likely results in highly correlated decisions due to the possibility to quickly react to other group members' behaviour. Thus, individual decisions cannot be considered statistically independent within one group. Second, and more importantly, the experimental design, particularly the resource growth function, does not allow to infer from high extraction rates low cooperation or coordination within a group. For example, if the resource stock is above the MSY, it is optimal to extract the maximum. By focusing on group outcomes at specific, preregistered, time points we circumvent these challenges.

While environmental ambiguity is present in both the LA and HA treatment until the break at 58 s, the two treatments differ in the level of ambiguity, as only participants in LA receive information about the range of the threshold. As discussed above, empirical and theoretical work remains inconclusive regarding the impact of different levels of environmental ambiguity on cooperation. On the one hand, lower ambiguity in the LA treatment may lead to higher cooperation levels than the HA treatment, in line with previous findings that focused on uncertainty in the form of risk regarding the resource size (Botelho et al., 2014; Budescu et al., 1992; Budescu et al., 1990; Gustafsson et al., 2000; Gustafsson et al., 1999; Kidwai and de Oliveira, 2020).[4] On the other hand, lower ambiguity could lead to lower cooperation levels for the following reason. Groups in HA may be more cautious in their extraction strategies, as driving the resource close or below the MSY may already result in a collapse. In contrast, groups in LA knew the threshold range (700 to 200 units) from the beginning. Therefore, they knew with certainty that it was safe to drive the resource even below the MSY. The focal point of the MSY may be thus replaced in LA with the upper bound of the threshold range. Such an effect is also suggested by theoretical work (Aflaki, 2013; Diekert, 2017) and by the empirical findings of Ahsanuzzaman et al. (2022). The latter compare resource extraction behaviour under threshold risk and ambiguity and find that extraction is lower under ambiguity than risk. Based on the different directions of possible effects and the dearth of empirical studies comparing different levels of ambiguity, we do not presume a clear direction of the treatment effect and hypothesize:

Hypothesis 1. Ambiguity about the location of the threshold affects *cooperation failure* measured as overexploitation of the resource. Groups in the LA treatment are either (a) *more* likely to overexploit and have a *higher* level of overexploitation or (b) *less* likely to overexploit and have a *lower* level of overexploitation than groups in HA.

We consider a resource level below the MSY - at the time of the pause (58 s) - as overexploitation and take this as a proxy for the failure of cooperation. In principle, non-cooperation can involve keeping the resource above or below the MSY, as underexploitation and overexploitation imply that group earnings are not maximized. However, because participants in the HA treatment had no information on the exact threshold before the pause, they did not know that the critical threshold was below the MSY. Hence, defining a resource level that constitutes under-exploitation in HA is not straightforward. Given these structural differences between treatments, our primary analysis focuses on cooperation failure by overexploitation, i.e., resource levels below the MSY.

Because the graphic representation of the resource development in the experiment made it difficult for participants to judge the exact level of the resource within a range of 30 units, we conservatively consider a resource stock of 970 units as MSY (instead of 1000). We define two outcome variables. First, a binary variable for cooperation failure equals 1 if the resource is below 970 resource units at 58 s, and 0 otherwise. Second, we define the level of overexploitation as a continuous variable, which measures the distance of the resource level to the MSY (970 units) at 58 s. The maximum overexploitation at the pause is 370 if the resource is at the lowest possible level (600 units). The minimum value for this variable is zero.

Furthermore, we are interested in what happens when the uncertainty is eventually resolved, i.e. when the exact location of the threshold is revealed. We hypothesize treatment differences in ambiguity about the threshold might persist after the uncertainty is resolved, due to the path-dependency of decision-making. If we observe a difference in cooperation between LA and HA (Hypothesis 1), the treatment

[4] Please note that Maas et al. (2017) – who compared different degrees of location of the threshold risks – did not find that different degrees affect coordination failure.

with relatively higher (lower) cooperation levels likely generates stronger (weaker) mutual trust in fellow group members. Lower trust in the willingness to cooperate could reinforce a "use-it-or-lose-it"-mentality (Crépin et al., 2012). Participants would likely anticipate that the group's extraction strategy will cause a collapse of the resource, leading individuals to increase their extraction and overexploit the resource intentionally to not miss out on their individual gain (Maas et al., 2017). Less cooperation and higher levels of overexploitation would then lead to a higher rate of coordination failure.

In addition to the trust mechanism, higher (lower) cooperation under ambiguity also affects the distance of the resource to the threshold once the exact threshold becomes known. Experiments focusing on endogenously induced scarcity of CPR – without modelling a threshold in their resource regrowth dynamics – may be informative about potential effects. Being comparably close to the threshold may alarm participants and motivate them to reduce their extraction, thus allowing groups to avert the resource collapse. Lab experiments have shown that resources user reduce their extraction when scarcity increases, but eventually fail to avert the depletion (Osés-Eraso et al., 2008). However, being close to the threshold may also increase the perceived competition over a scarce resource as found by experiments with resource users in Namibia (Hoenow and Kirk, 2021). In sum, while we outlined potential mechanisms for how the level of ambiguity about threshold location may affect coordination once the uncertainty is resolved, the direction of this effect is unclear. Thus, we formulate:

Hypothesis 2. Differences in prior ambiguity about the location of the threshold affect *coordination failure*, i.e., the likelihood of the resource collapsing once the critical threshold is revealed. Groups in LA are either (a) *more* or (b) *less* likely to cause a collapse of the resource than groups in HA.

We measure coordination failure as a binary variable 'collapse of the resource', defined as equal one if the resource level reached or fell below the threshold of 400 resource units and thus collapsed, and zero otherwise. We assess this variable at three points: at our defined endpoint for analysis purposes (210 s) and at two earlier control times (90 and 150 s).

2.4. Data collection

The experiment was implemented at the WISO Experimental Lab of Hamburg University between November 2019 and February 2020 and was programmed in the experimental software SoPHIE (Hendriks, 2012). We obtained ethical clearance prior to data collection based on the scientific and ethical standards of the WiSo Laboratories at the Faculty of Business, Economics and Social Sciences of Hamburg University. Participants provided their free, informed consent prior to participation. For 17 sessions, 360 participants were recruited from the pre-registered subject pool. We had 180 participants, i.e., 45 groups per treatment. Each participant only participated in one of the two treatments. On average, participants earned 14.7 Euro (SD = 5.5, Min = 2.2, Max = 35.2), and each session lasted about 75 min.

Participants played two practice rounds of 90 s in groups of four before the payout-relevant round of at least 240 s. The practice rounds allowed participants to familiarize themselves with the resource dynamics and the mechanism of resource extraction. In contrast to the payout-relevant round, the practice rounds had a certain end and did not incorporate a critical threshold.

We randomized the two treatments at the group level within experimental sessions. For the payout-relevant round, two members of each test round group were assigned to HA and two to LA. Furthermore, we implemented a perfect strangers' matching such that participants who were group members in the practice rounds did not interact with each other again in the payout-relevant round. All participants knew this. Thereby, we reduced social learning effects and avoided strategic interactions and reputation building between test and payout-relevant rounds (Andreoni, 1988). More details on the implementation are provided in SI, Section B, and the experimental instructions, including the post-experimental questionnaire, are provided on the Open Science Framework (OSF; Link).

Participants had to answer control and feedback questions at two points to check their understanding of the experiment. Before the practice rounds, participants had to answer three control questions to ensure their understanding of the resource development and the extraction mechanism. Next, they had to answer four additional control questions after they received the threshold information, i.e., before they started playing the payout-relevant round. Participants needed, on average, one attempt to answer all control questions correctly (SD = 0.2), which indicates a good understanding. Furthermore, individuals rated the instructions and the understanding of the resource development on a 5-point Likert scale as part of the post-experimental questionnaire (1: "strongly reject"; 5: "strongly approve"). On average, respondents considered the instructions to be well written (Mean = 4.5, SD = 0.8) and stated that they understood the resource development well (Mean = 4.4, SD = 0.9).

We find no statistically significant differences in participants' sociodemographic characteristics and understanding of the experiment between the two treatments (SI, Table C.1). Participants' average age was 25.5 years (SD = 4.8), the total fraction of female participants was 62.8% ($N = 226$). The monthly median income was between 601 and 900 Euro (average category = 2.8, SD = 1.2). The total fraction of economics students was 28.9% ($N = 104$), and 89.4% (SD = 322) have had previous experience in economic or psychological experiments. The average risk-taking measured on an 11-point scale (Dohmen et al., 2011) was 5.2 (SD = 2.2). The average expectation of the round's continuation beyond the certain minimum round length is significantly different between the two treatments. Individuals in LA expect the round to continue longer than groups in HA (two-sided t-test: $p < 0.01$, SI Table C.1). We do not expect this to affect our results because we define 210 s as the endpoint for the analysis. Nonetheless, we include this control variable in the regression analyses reported in the SI, Section D and E.

3. Results

We pre-registered the study at "aspredicted.org" (Link) and deviate at two points from the pre-registration. First, to account for some of the variance in the outcomes, we run robustness checks of our regression models, including groups' mean age, the fraction of females, mean risk measure, and mean expected continuation of the round as controls. The results are reported for brevity in the SI, Section D, and E. Second, we pre-registered analysis based on a continuous measure of coordination, namely the distance of the resource from the threshold. We do not consider this as an adequate measure of coordination anymore, as coordination should be rather understood as a dichotomous outcome. A higher resource level does not correspond to a higher level of coordination. The results of this analysis are reported in the SI, Section F. We do not find any significant treatment differences with this additional outcome. Exploratory analysis that was not part of the pre-registration is explicitly labelled as such in the remaining article.[5]

3.1. Resource development and group extraction over time

Fig. 2 shows the time trends of the average resource development and extraction levels per treatment. On average, groups start with relatively high levels of resource extraction, as the resource is in the beginning far above the MSY level and it is thus optimal to extract the

[5] In SI, Section I, we report correlation between risk preferences and cooperation and coordination outcomes. We do not report this analysis in the main article, as we elicited risk preferences only after the experiment with a survey question. We refer interested readers to the SI.

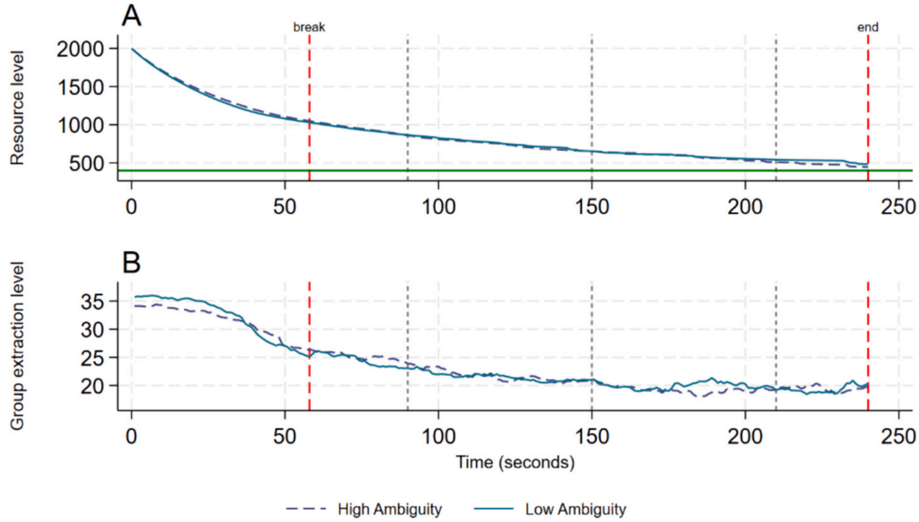

Fig. 2. Average resource stock level over time (0 to 240 s) (Panel A) and the corresponding average group extraction levels per second over time (Panel B) by treatment (i.e. line type). The red vertical line at 58 s marks the time of the pause, and the red line at 240 s marks the minimum round length (end). The three grey dashed vertical lines at 90, 150, and 210 s mark the three times at which we analyse groups' level of coordination. The green horizontal line in Panel A indicates the threshold. Fig. H.1 in the SI illustrates the corresponding individual group trajectories separated by experimental treatment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

maximum. Between the seconds 30 and 40 one observes a clear decline in the extraction rates as groups become more cautious as approaching the MSY level. While group extraction declines – on average – over time, the reductions are not sufficient to avert the steady decline of the average resource levels. Fig. H.1 in the SI, provides the corresponding group-level trajectories. Here, one can observe that some groups maintain the resource level above the threshold and relatively close to the MSY level in both treatments.

The resource development over time is almost identical for the two treatments (Panel A). Differences are more discernible in the groups' chosen extraction levels over time (Panel B). Groups in HA seem to be more cautious at the start and have set slightly lower average extraction levels at the very start of the round than groups in LA (HA: Mean = 34.1, SD = 5.4; LA: Mean = 35.7, SD = 4.3). However, this difference is not statistically significant (two-sample Mann–Whitney–Wilcoxon test: z = −1.28, p = 0.20).

3.2. Cooperation with threshold ambiguity

The majority of groups in both treatments successfully cooperated until the pause. Only 20% of the groups in HA (N = 9) and 24% of the groups in LA (N = 11) overexploited the resource below 970 resource units in the pre-pause phase. Maximum group extraction from the beginning would have driven the resource below the MSY after about 40 s. We find no statistically significant difference in the proportion of groups that overexploited the resource between the two treatments (two-sided Fisher's exact test: p = 0.8). Probit regressions yield the same results (SI, Table D.1).

We proceed to analyse the *degree* of groups' overexploitation. As explained above, this outcome measure ranges from zero if groups cooperated (keep the resource above 970) to 370 if groups failed to cooperate and drive the resource to the lowest possible level (600). We find no statistically significant difference in the degree of overexploitation between the two treatments (HA: Mean = 19.3, SD = 52.2, Min = 0, Max = 235.7; LA: Mean = 17.1, SD = 40.1, Min = 0, Max = 182.0; two-sample Mann–Whitney–Wilcoxon test (MWW): z = −0.43, p = 0.67). Again, Tobit regressions confirm this result (SI, Table D.2). Hence, we find no evidence that lower ambiguity in the form of threshold range knowledge affects cooperation amongst resource users. We thus do not find support for Hypothesis 1.

3.3. Between- and within-group variation

As indicated in the hypotheses section, lower ambiguity regarding the location of the threshold may result in two opposing dynamics. If lower ambiguity would trigger these two opposing dynamics, we would expect a higher variation in observed resource extraction levels, without observing a difference between treatments on average. Because these dynamics could be manifested at either the group or individual level, we conduct analysis on both between- and within—group variation in extraction levels.

The development of the between-group standard deviation in average resource extraction is illustrated in Fig. 3, Panel A. Overall there is no clear tendency that the between-group variation is systematically different between the two treatments. At the beginning t = 1 s, the standard deviation between groups in HA is somewhat larger than in LA (1.35 vs 1.09, Brown–Forsythe test: p = 0.266). At the time of the break, at t = 58 s, treatment differences are less pronounced (1.18 vs 1.1, Brown–Forsythe test: p = 0.798).

The development of the average within group variation in resource extraction is shown in Fig. 3, Panel B. Within-group variation in extraction is generally lower in the LA treatment, in particular at the beginning of the experiment and towards the very end. At the beginning, at t = 1 s, the average within-group standard deviation in extraction is larger in HA (1.89) than LA (1.43), a difference that is not significant (MWW: p = 0.107). At t = 58 s, the time of the break, variation has overall increased, but treatment differences are smaller (HA 2.43, LA 2.24; MWW: P = 0.458). In pooled regression analysis, we observe a marginally significantly smaller within-group variation in LA (see SI, Table H.1).

Overall, these results do not suggest that the LA treatment leads to two opposing effects either within or between groups, which could have generated the observed null result that different levels of threshold ambiguity do not affect cooperation behaviour. At best, we find support for the opposite as within-group variation in extraction tends to be smaller in LA than HA.

3.4. Coordination under threshold certainty

In the following part, we focus on the period after the pause when the exact threshold is known for both treatment groups. Fig. 4 presents the

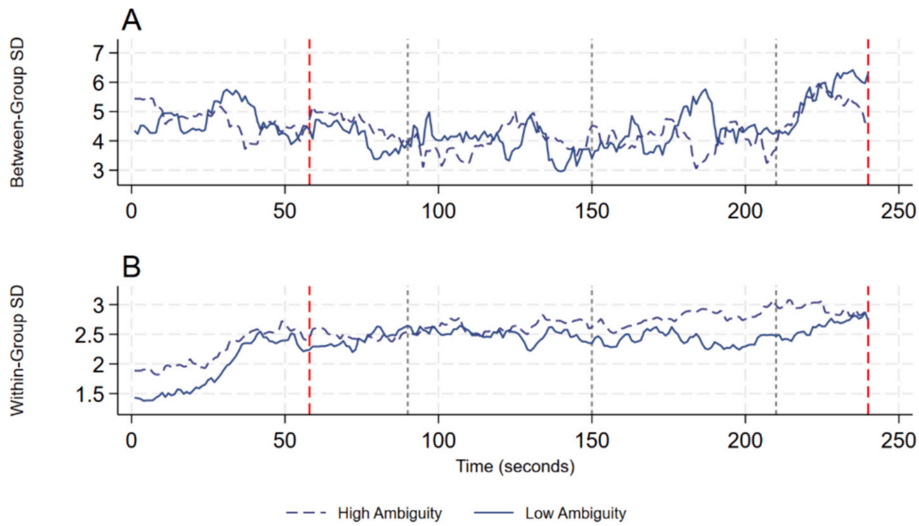

Fig. 3. Development of the between-group standard deviation in average extraction (Panel A) and of the average within-group standard deviation of extraction (Panel B) over time (0–240 s) by treatment (i.e. line type). The red vertical line at 58 s marks the time of the pause, and the red line at 240 s marks the minimum round length (end). The three grey dashed vertical lines at 90, 150, and 210 s mark the three times at which we analyse groups' level of coordination. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

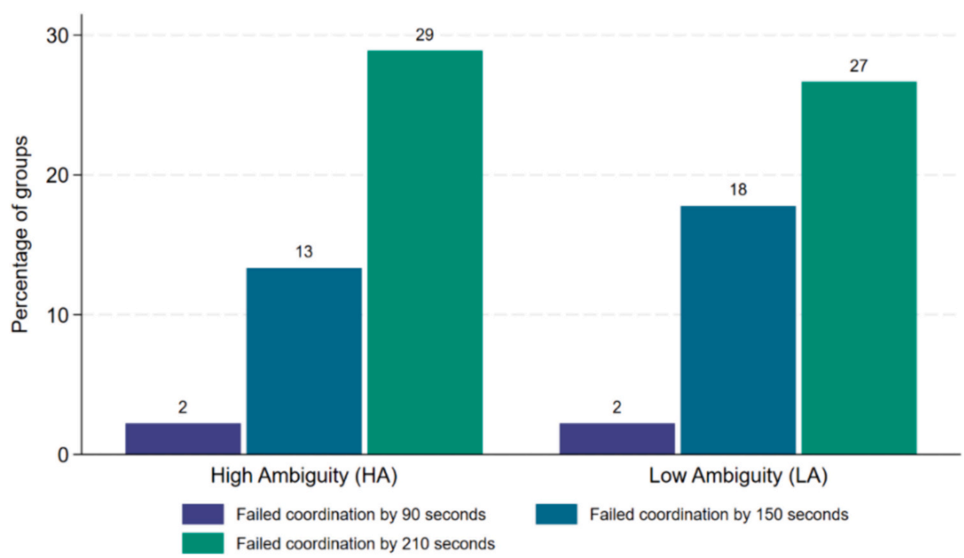

Fig. 4. The percentage of groups with coordination failure at $t = 90$, $t = 150$, and $t = 210$ s per treatment 'High Ambiguity (HA) and 'Low Ambiguity (LA). Coordination failure is defined as the crossing of the threshold and subsequent collapse of the resource.

percentage of groups that failed to coordinate and caused a collapse of the resource at three time points. At 90 s, only one out of 45 groups (2%) in each treatment failed to coordinate, causing an early collapse. At 150 s, more groups in LA (18%) than HA (13%) failed coordination. At 210 s, however, more groups in HA (29%) than LA (27%) caused the resource to collapse. None of these differences between treatments are statistically significant (SI, Table E.1). Furthermore, we find no significant treatment effects in Probit regressions with the failure of coordination as the dependent variable (SI, Table E.2). Thus, we find no evidence that different levels of prior threshold ambiguity increase or decrease coordination failure after the certain threshold is known. Consequently, we do not find support for Hypothesis 2.

We conducted an exploratory analysis of cooperation at 90, 150, and 210 s to shed further light on behavioural differences after resource users know the threshold with certainty. Overall, overexploitation as a measure of failed cooperation increases over time. Nevertheless, we find no significant differences between treatments at any of the analysed times (SI, Table G.1). We further find no significant treatment effects in Tobit regressions with the degrees of overexploitation at the given times as dependent variables (SI, Table G.2).

3.5. Behavioural changes after threshold certainty

To investigate whether the impact of threshold certainty was different between treatments, i.e. levels of prior threshold ambiguity, we provide further exploratory analysis of the behavioural change right after the break. Most participants did not change extraction levels after the break (overall: 39.7%, HA: 36.1%, LA: 43.3%), 32.2% increased (HA: 33.3%, LA: 31.1%), and 28.1% decreased extraction (HA: 30.56%, LA: 25.6%). Differences between treatments are not statistically significant (Chi-Squared Test: $p = 0.346$). The distribution of extraction decisions for each treatment before and after the break are shown in Fig. 5. In HA, the largely overlapping distributions indicate – on aggregate - little changes during the break. In LA, less respondents than in HA

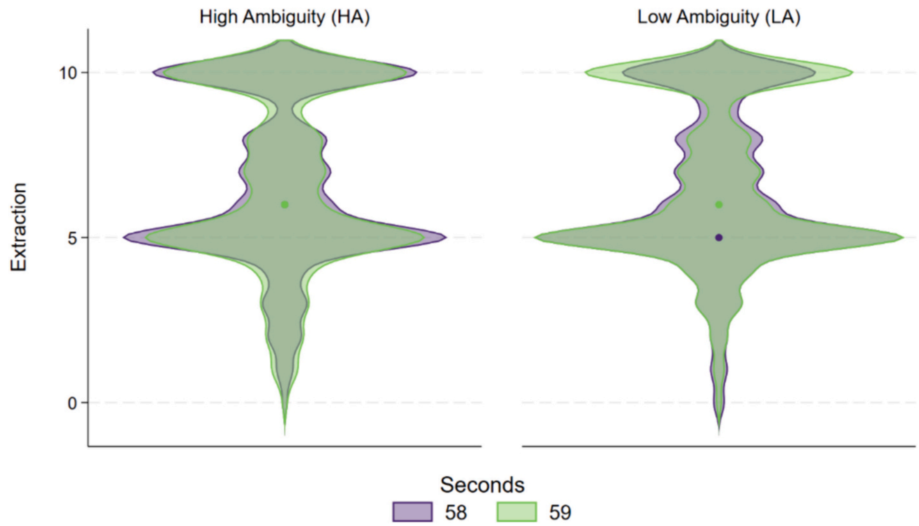

Fig. 5. Overlaid violin plots of individual extraction decisions before (t = 58) and after the break (t = 59 s) by treatment group.

extracted the maximum before the break, while these differences disappear after the break. However, neither before nor after the break average extraction is significantly different between treatments (before break: MWW p = 0.226, after break: MWW p = 0.98). These findings again corroborate minor differences in behaviour both under threshold ambiguity and later on under threshold certainty.

3.6. *Exploratory analysis: Factors explaining coordination and cooperation in the long-run*

While our results indicate that the different levels of ambiguity do not affect the likelihood for groups to cooperate nor to coordinate, we proceed to further explore factors that determine the success of groups in terms of both cooperation and coordination in the long term, i.e., towards the end of the experiments at t = 210 s.

Only 8.9% (8) of the groups sustain the resource at the MSY (i.e. cooperate) at t = 210 s. At this point, 27.8% of groups (25) failed to coordinate and caused the resource to collapse. We run individual probit regression models with different explanatory variables to explore if specific group characteristics are correlated with successful cooperation and coordination. The results are shown in Fig. 6. Overall, we find that whether a group successfully cooperated until the break at t = 58 s, has a significant and positive impact on the likelihood to coordinate later. We also find that the within-group standard deviation in extraction levels at t = 150 s has a significant negative impact on the coordination and cooperation likelihood. Groups with a larger number of changes in the

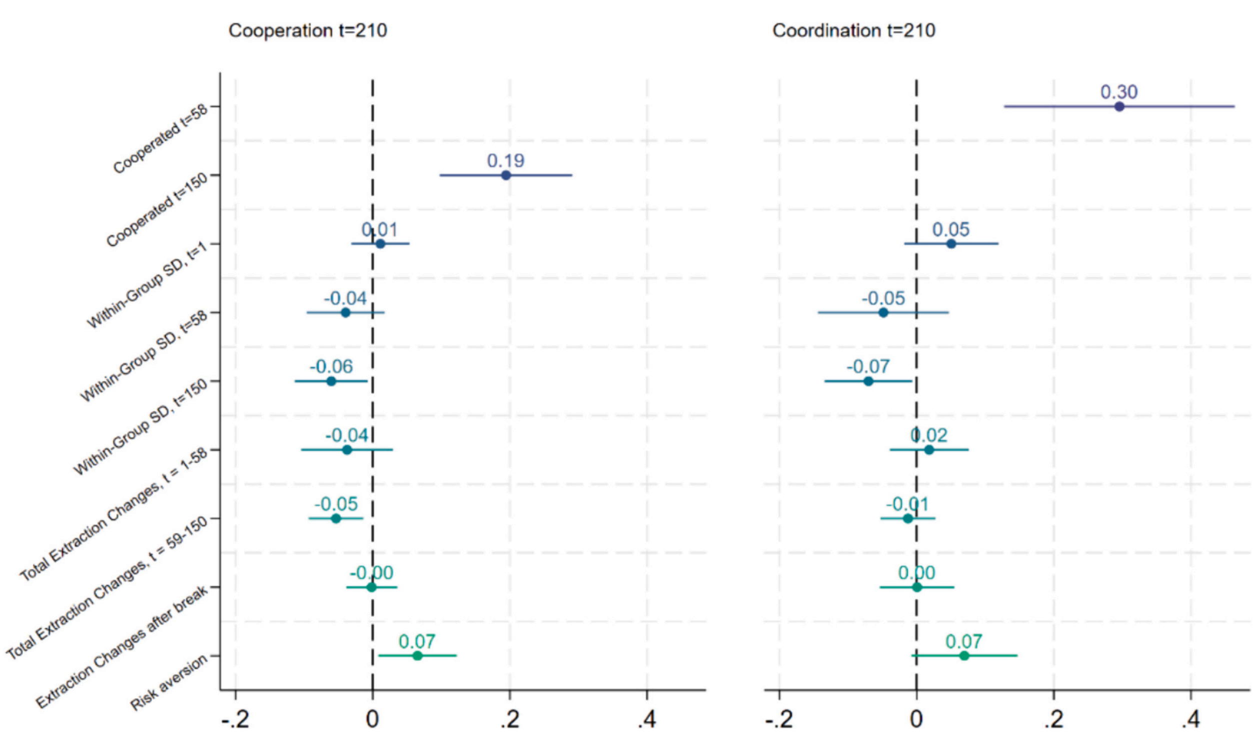

Fig. 6. Correlation between cooperation and coordination outcome at the end of the experiments (t = 210 s) and explanatory variables. The point estimates and 95% Confidence Intervals are derived from separate Probit regression models reported as marginal effects. The effect size indicates the change in the likelihood to coordinate/cooperate due to a one unit increase in the explanatory variable. The effect of 'Cooperated, t = 58' and 'Cooperated t = 150' cannot be estimated for the Cooperation and Coordination outcome respectively, because they perfectly predict the outcomes.

extraction levels after the break, are also less likely to cooperate. We also find that more risk averse groups are on average more likely to cooperate at the end of the experiment. The impact of risk aversion on coordination is similar in size, but only marginally significant ($p < 0.1$).

4. Discussion

Previous studies on the effect of environmental uncertainty regarding critical thresholds on resource management did not compare different levels of ambiguity. We contribute to filling this gap, by developing a novel (quasi-) continuous-time CPR lab experiment with two treatments varying the level of ambiguity about the threshold location. Under high ambiguity, participants merely knew of the threshold's existence. Under low ambiguity, participants knew the range where the threshold is located, but did not know the probability distribution within this range. We do not find evidence that the level of ambiguity impacts cooperation. Unlike higher uncertainty in the form of risk about the resource size (Budescu et al., 1992; Budescu et al., 1990; Gustafsson et al., 2000; Gustafsson et al., 1999; Kidwai and de Oliveira, 2020), higher levels of ambiguity regarding the location of the threshold seem to not lead to higher CPR extraction rates and less cooperation. One explanation for this null effect could be that lower ambiguity about the threshold can conceptually have positive as well as negative effects on cooperation, as outlined above. Thus, if both sets of conceptual arguments were true, these opposing effects could offset each other, leading to a null effect on the treatment level. However, exploratory analysis of the within- and between-group variation in resource extraction between treatments does not support this argumentation. An alternative explanation could be that the positive impact of threshold information (in the form of reduced threshold ambiguity) fosters cooperation and coordination only if this additional information reduces uncertainty below a certain level. Our 'low ambiguity' treatment may simply still include too much ambiguity to affect behaviour relative to scenarios with more ambiguity. This interpretation is also in line with the findings of Ahsanuzzaman et al. (2022) and Dannenberg et al. (2015), who found insignificant differences in cooperation and coordination outcomes after comparing scenarios with threshold location risk and threshold location ambiguity. Compared to previous CPR (Ahsanuzzaman et al., 2022; Schill et al., 2015; Lindahl et al., 2016; Maas et al., 2017) and TPG experiments (Barrett and Dannenberg, 2012, 2014b) that focused on other dimensions of threshold uncertainty, we have a comparably large sample size. Our study should be thus sufficiently powered to find similar effect sizes.

Furthermore, we find no evidence that different prior levels of ambiguity affect group coordination once the exact threshold is known. The associated hypothesis rests on the assumption that path dependency creates different trajectories by affecting trust and/or the distance to the threshold. As we did not find any treatment difference in the first part of the experiment where ambiguity existed, the null effect is not surprising.

Our findings may be contingent on several experimental design features that we discuss here, as this may provide interesting avenues for future research. First, in contrast to other studies incorporating thresholds (uncertainty) both in the lab (Lindahl et al., 2016; Schill et al., 2015) and field (Rocha et al., 2020; Schill and Rocha, 2023), participants in our experiment were unable to communicate with each other. Schill et al. (2015) and Lindahl et al. (2016) find that the threat of reaching a critical threshold triggers better communication within groups and increases the likelihood for groups to reach agreements about resource extraction levels. Future experiments could allow for communication and analyse whether different ambiguity levels affect both communication and extraction strategies. Second, to test our second hypothesis regarding the lasting impact of ambiguity on extraction behaviour once the location of the threshold is revealed, groups faced ambiguity only for a limited time. Even though it was possible to drive the resource below the cooperative equilibrium (MSY), the time may not have sufficed to result in treatment differences. In the design process, we decided to limit this time so that groups could not cross the threshold and collapse the resource in order to assure sufficient statistical power for testing the second hypothesis. Future studies could adapt a design that provides more scope for treatment differences, by allowing more time to pass under different ambiguity levels. Third, our results could be contingent on our chosen threshold range that was relatively wide. Previous evidence based on a TPG game where participants knew the underlying probability distribution of the threshold suggests that cooperation and coordination improve the smaller the range of the threshold is (Barrett and Dannenberg, 2014b). Further research is warranted to assess whether different levels of ambiguity regarding the threshold location – implemented as different ranges for possible threshold locations - affects resource management. Here, experiments ideally implement several treatments, also with narrower ranges compared to our low ambiguity treatment.

While previous studies have found that uncertainty about the threshold results in lower cooperation and coordination relative to a certain threshold (Ahsanuzzaman et al., 2022; Barrett and Dannenberg, 2014a, 2014b; Barrett and Dannenberg, 2012; Brown and Kroll, 2017; Dannenberg et al., 2015; Maas et al., 2017), we observe - despite ambiguity - relatively high levels of coordination and cooperation. These results mirror previous evidence from lab-in-the-field experiments with actual resource users: Rocha et al. (2020) and Schill and Rocha (2023) find little differences between scenarios without a threshold, with a certain threshold, and with uncertain and ambiguous thresholds. One explanation is that actual resource users who participate in lab-in-the-field experiments take context from the more complex reality of resource management into simplified experiments. By implementing a continuous-time CPR experiment in the lab, cooperation amongst students possibly reached similarly high levels of cooperation as observed in the field with communication (Lindahl and Jarungrattanapong, 2023; Rocha et al., 2020; Schill and Rocha, 2023). Indeed, a systematic comparison of discrete and continuous-time CPR experiments found that cooperation is higher in continuous-time designs (Djiguemde et al., 2022). The impact of threshold ambiguity on cooperation might be in a setting with already relatively high cooperation levels comparably small. We did not implement a treatment with a certain threshold, so this finding remains somewhat speculative (as we base this argument on the absolute levels of behaviour observed in our experiment). We consider this a promising avenue for future research, in particular studying if the effect of threshold uncertainty (both risk and ambiguity relative to certainty) is different under specific experimental designs (communication vs. no communication, discrete vs continuous) that have been shown to influence the propensity to cooperate.

Our lab experiment is based on a sample of western, highly educated students from a high-income country and results should be interpreted with this caveat in mind. The question to what extent our findings provide valuable insights for actual CPR management, relates to the broader debate in experimental economics about external validity (Al-Ubaydli and List, 2015; Camerer, 2015). Generally, lab experiments allow for a greater degree of control compared to lab-in-the-field experiments with actual resource users, who bring their past experiences with the resource and fellow resources users to the experiment. Such experiences may also result in fundamentally different behavioural responses. Prior experiments with actual fishers have, for example, found diverging effects of resource thresholds on behaviour (Lindahl and Jarungrattanapong, 2023; Rocha et al., 2020). We consider it therefore imperative to replicate our study in field contexts to generate more robust knowledge.

5. Conclusion

Ecosystems are under endogenous and exogenous pressure, for example, through overexploitation and climate change. Thus, they become more likely to reach critical thresholds causing regime shifts to less favourable states (Scheffer et al., 2001). Yet, scientific knowledge of critical thresholds often remains vague and is commonly associated with different uncertainties. While a growing body of research has focused on different levels of thresholds risks, only a few studies have focused on higher levels of uncertainty in terms of ambiguity (Ahsanuzzaman et al., 2022; Hine and Gifford, 1996; Schill and Rocha, 2023) and none of them compared different levels of ambiguity. Our experiment focused on the impact of varying levels of ambiguity regarding the threshold location on cooperation and coordination in resource management. We do not find evidence that different levels of threshold location ambiguity affect resource extraction and cooperation. We also do not see a lasting effect of different ambiguity levels on coordination after the uncertainty is resolved.

Based on our findings, we conclude that a reduction in threshold ambiguity - as we designed it - does not affect resource management outcomes. These findings are also in line with prior studies that compared scenarios with different degrees of risks (Maas et al., 2017; Schill et al., 2015) and find that less uncertainty does not affect CPR management outcomes. Minor behavioural differences are also observed by Ahsanuzzaman et al. (2022), who compare threshold location risk with ambiguity. Taken together these findings suggest that a reduction in uncertainties about threshold location is unlikely to affect CPR management as long as some residual threshold uncertainties prevail. From a policy perspective, it appears more beneficial to increase general awareness amongst a broader range of resource users about critical thresholds rather than concentrating on providing more accurate information to reduce threshold uncertainty.

CRediT authorship contribution statement

Katharina Hembach-Stunden: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Tobias Vorlaufer:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Stefanie Engel:** Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

The authors have no financial or non-financial conflict of interest.

Data availability

The experimental material, replication data, and analysis scripts are available on the Open Science Framework (https://doi.org/10.17605/OSF.IO/WEAYH).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2024.108353.

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