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Fragility of the commons under prospect-theoretic risk attitudes ☆

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ABSTRACT

We study a common-pool resource game where the resource experiences failure with a probability that grows with the aggregate investment in the resource. To capture decision making under such uncertainty, we model each player's risk preference according to the value function from prospect theory. We show the existence and uniqueness of a pure Nash equilibrium when the players have heterogeneous risk preferences and under certain assumptions on the rate of return and failure probability of the resource. Greater competition, vis-a-vis the number of players, increases the failure probability at the Nash equilibrium; we quantify this effect by obtaining bounds on the ratio of the failure probability at the Nash equilibrium to the failure probability under investment by a single user. We further show that heterogeneity in attitudes towards loss aversion leads to higher failure probability of the resource at the equilibrium.

1. Introduction

Common-pool resources (CPRs) are a broad class of shared resources characterized by two properties. First, they are non-excludable, meaning that it is (practically) infeasible to prevent any user from accessing them. Second, they are rivalrous or subtractable: higher use by one user leads to less availability for others. Selfish or myopic decision making by users competing for a CPR often results in suboptimal outcomes (including potential destruction of the resource) for the entire group; prominent examples include collapse of fish stocks due to overfishing (Walker and Gardner, 1992) and global warming due to greenhouse gas emissions (Ostrom et al., 1999). In his seminal paper, Hardin popularized the phrase "Tragedy of the Commons" to refer to such outcomes (Hardin, 1968).

In this paper, we study a game-theoretic setting of a CPR where the resource experiences probabilistic failure due to overutilization. The possibility of resource failure leads to uncertainty in the outcomes for the players. In this context, the risk preferences of the players can have a significant impact on their actions, and consequently on the uti-

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lization and fragility of the resource. Studies from behavioral economics show that individuals are typically neither risk neutral nor classical expected utility maximizers (Von Neumann and Morgenstern, 1947) when making decisions under uncertainty, and instead exhibit complex risk attitudes (Machina, 1987). One of the most widely accepted behavioral models of decision making under probabilistic uncertainty is "Prospect Theory" (Kahneman and Tversky, 1979; Tversky and Kahneman, 1992), where loss or gain of utility is measured with respect to a reference utility. Individuals exhibit risk seeking behavior under losses and risk averse behavior under gains, giving rise to an S-shaped utility function; this characteristic of the utility function is known as "diminishing sensitivity." Furthermore, under prospect-theoretic preferences, the decrease in utility under loss of investment is typically greater than the increase in utility under a gain of the same magnitude; this behavior is popularly known as "loss aversion." Thus, prospect-theoretic utility functions account for these systematic (and experimentally observed) deviations in human behavior from the predictions of the classical expected utility theory framework.

While prospect theory has been applied in diverse settings involving decision making under risk, including finance, insurance, industrial organization and betting markets (see Barberis, 2013 for a review), theoretical analysis of prospect-theoretic preferences has been more recent and growing (Butler, 2007; Baharad and Nitzan, 2008; Leclerc, 2014; Easley and Ghosh, 2015). As we discuss in Section 1.2, certain prospect-theoretic characteristics such as framing effects, reference dependence and loss aversion have been observed, often in isolation, in past experimental studies related to CPR games. However, most of the (theoretical) investigations of CPR games have not considered prospect-theoretic risk attitudes, focusing instead on risk neutral and classical expected utility maximization behavior while modeling the risk preferences of human beings. Both of the above frameworks are typically more tractable to analyze compared to prospect theory. Understanding the effects of behavioral risk preferences in settings that model tragedy of the commons phenomena remains largely unexplored. Thus, given its strong behavioral foundations and experimental evidence from related settings, we model players' risk preferences according to the value function from prospect theory and study the effect of these risk preferences on the decisions made by players competing for a failure-prone CPR (where the uncertainty faced by each player arises from the potential failure of the shared resource).

Our formulation builds upon well established game-theoretic models for CPR sharing (Ostrom et al., 1994; Budescu et al., 1995a). In the standard CPR game (Walker et al., 1990), players start with an initial endowment and choose their investments in two resources; one of the resources has a constant return on investment (safe resource), while the other is a CPR with a rate of return function (to be precisely defined in Section 2) that is decreasing in the total investment in the resource.[1] Walker and Gardner (1992) studied probabilistic resource failure in a repeated CPR game, where the CPR could fail in any iteration with a probability that is a linearly increasing function of the aggregate investment by the players in that iteration. In their setting, players are assumed to be risk neutral and maximize the expected sum of utilities across a fixed and finite number of iterations.

Failure of a shared resource has been explored in greater detail in a related game-theoretic setting referred to as the "resource dilemma" problem (Suleiman and Rapoport, 1988; Rapoport and Suleiman, 1992; Budescu et al., 1995a). Here, the players participate in a single stage game where they choose their level of consumption from a resource of an unknown size (drawn from a prior probability distribution, typically taken to be the uniform distribution on a given interval). If the total consumption requested by the players is less than the size of the resource, the players receive their requested amount; otherwise, none of the players receive any benefit. Budescu et al. (1995a) model the risk preferences of players using the classical expected utility maximization framework, which captures risk averse (or risk seeking) behavior with a concave (respectively, convex) utility function.[2]

In the present work, we consider a single stage standard CPR game with resource failure. Players split their investments between a fragile CPR and a safe resource. If the CPR does not fail, each player receives a return that is proportional to her own investment and the rate of return of the CPR. If the CPR fails, the players receive no return from it. We model the failure probability of the CPR as an increasing and convex function of the total investment in the CPR. This includes failure probability functions that are linearly increasing within an interval, capturing the setting in resource dilemma problems (Budescu et al., 1995a) where the resource size is drawn from an interval uniformly at random. The convexity assumption is also motivated by the characteristics of many complex systems that undergo a sharp transition from one state to another with only a small change in the environment around a threshold, often referred to as a "tipping point" of the system (Gladwell, 2006; Lenton et al., 2008; Rockström et al., 2009; Scheffer, 2009). Convex failure probability functions are of interest since they can approximate a sharp transition of the resource from a safe state (one with a small failure probability) to a fragile state (marked by failure probability close to one) with a relatively small change in the underlying investment.

Our analysis captures CPRs with both decreasing and increasing rate of return functions. Examples of resources with decreasing rate of return functions can be found in both natural and engineered systems such as fisheries, groundwater basins, forests (Ostrom et al., 1994) and communication/traffic networks (Nisan et al., 2007). Such resources are said to

[1] Ostrom et al. (1994) studied how individuals behave in controlled experiments for different variants of this standard CPR game, how their strategies compare to the outcome predicted by Nash equilibrium strategies, and what mechanisms lead to greater cooperation among players.

[2] The main focus of this line of work has been to study the effect of uncertainty (e.g., Aflaki, 2013), and game structure (such as the order of investments by the players (Budescu et al., 1995b)) on the equilibrium outcome.