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Strategic exploitation of a common-property resource under uncertainty ☆

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ABSTRACT

We construct a game of noncooperative common-resource exploitation which delivers analytical solutions for its symmetric Markov-perfect Nash equilibrium. We examine how introducing uncertainty to the natural law of resource reproduction affects strategic exploitation. We show that the commons problem is always present in our example and we identify cases in which increases in risk amplify or mitigate the commons problem. For a specific class of games which imply Markov-perfect strategies that are linear in the resource stock (our example belongs to this class), we provide general results on how payoff-function features affect the responsiveness of exploitation strategies to changes in riskiness. These broader characterizations of games which imply linear strategies (appearing in an Online Appendix) can be useful in future work, given the technical difficulties that may arise from the possible nonlinearity of Markov-perfect strategies in more general settings.

1. Introduction

In games of common-property renewable resource exploitation each player partly controls the future evolution of the resource, given the strategies of other players. Models in which there is a dynamic element and in which resources are shared play an important role in economics, e.g., industrial organization models or models with natural resources. The fundamental, infinite-horizon setup, in which all players have full information about the economic environment, has been studied in the economics literature almost exclusively within the deterministic framework. The main finding of this literature is that the equilibrium is characterized by a "commons problem". Namely, the higher the number of non-cooperating players, the higher the aggregate exploitation rate, so the lower the level of the resource in the long run.[1] Our goal in this paper is to examine how noncooperative strategic interaction is affected by uncertainty in the natural law of resource reproduction.

☆ A supplementary Online Appendix is available at the journal's repository of supplementary material which can be accessed via http://www.jeem-supplemental.org/.

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[1] See, for example, Mirman [16] and Levhari and Mirman [13], Levhari et al. [12], Benhabib and Radner [2], Dockner and Sorger [7], Sorger [21,22] and Koulovatianos and Mirman [11].

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Our focus on randomness in resource reproduction is a natural starting point for the study of uncertainty in resource games. In the real world, resources evolve according to stochastic laws of motion. Especially in the context of natural resources, as is the case with biological populations such as forests and fish species, these evolve subject to the existence of predators or climate, that are affected by random disturbances.[2]

Stochastic dynamic games can be particularly complex and difficult to characterize when the law of resource reproduction, the payoffs and the distributions of random disturbances are all given by general functions.[3] At the same time, the task of characterizing decisions in the presence of uncertainty in a general framework can be demanding even in the case of a single decision maker.[4] We discuss why technical problems arise in multiple-player dynamic games which use general functional forms. Specifically, in resource games problems arise because each player's objective function directly contains the strategies of other players. When the Markov-perfect Nash strategies of other players are strictly concave, a player's objective function may lose key properties, such as concavity, differentiability, and continuity. These technical difficulties are discussed in Mirman [16].

A special class of dynamic games avoids such technical difficulties related to the concavity of Markov-perfect Nash strategies. It is the class of games which possess primitives such that symmetric Markov-perfect Nash strategies are linear decision rules with respect to the common resource.[5] A game that falls in this class is the parametric example of Levhari and Mirman [13]. Yet, strategies in the Levhari and Mirman [13] example are unaffected by introducing uncertainty. Here we provide a new example that nests and extends the Levhari and Mirman [13] example, in which introducing uncertainty and risk changes (in terms of first- or second-order stochastic dominance) affect exploitation strategies.

Our analysis is extended to the case of N players, where N can be more than two players. A study that extended the Levhari and Mirman [13] model to $N>2$ players is Okuguchi [18], who has also emphasized the effects of entry (or exit) in fish war in comparison with cooperative solutions (joint resource management by all players). Understanding how noncooperative strategic behavior changes as we add players to a game is key to understanding whether, under particular forms of regulation, cooperation is sustainable as a subgame-perfect equilibrium.[6] Here, apart from presenting our example and performing comparative analysis of strategies as we increase risk, we do not provide extensions to resource regulations. We do, however, provide an Online Appendix which proposes theoretical tools in order to analyze the comprehensive class of games with primitives that allow for Markov-perfect Nash exploitation strategies which are linear in the resource stock.[7] These tools and theoretical results which are based on a stochastic-dominance analysis of how risk changes affect strategies are applicable to other examples of linear-Markov-perfect–Nash strategy games that one may discover along the way.

2. The general framework

Time is discrete and the horizon is infinite, i.e. $t=0,1,\ldots$. Let the state variable, x, evolve naturally (in the case of no exploitation) according to the law of motion,

$$x_{t+1}=\theta_t f(x_t). \tag{1}$$

We assume $f'>0$, $f''\le 0$. The random variable θ_t is i.i.d., independent of x_t and,

$$\theta_t \sim \Theta(\theta_t), \quad t=0,1,\ldots.$$

We assume that Θ, the distribution function of θ_t, has support $S_\theta \subseteq \mathbb{R}_+$ and mean $E(\theta_t)<\infty$, for all t.

We consider $N\ge 1$ identical players. In period t, each player $j\in\{1,\ldots,N\}$ consumes $c_{j,t}\ge 0$ units of the available stock, and then a realization of the random shock takes place. Next period's level of x is given by

$$x_{t+1}=\theta_t f\left(x_t-\sum_{i=1}^{N} c_{i,t}\right).$$

[2] In cases of governmental provisions of infrastructure for companies, such as railroads, electricity grids, telecommunication networks, etc., financing and maintenance is also subject to random shocks, such as business cycles or political cycles.

[3] An example of a study examining the link between extraction decisions and uncertain reproduction outcomes under perfect competition, and also optimal resource preservation policies, is the fishery application of Mirman and Spulber [17]. For a paper studying uncertainty and games see Amir [1]. For studies pointing out technical issues in *deterministic* differential resource games, such as multiplicity of equilibrium strategies, arising even in setups with some simplifying assumptions on primitives, see Dockner and Sorger [7], and Sorger [21], while for fundamental proofs of equilibrium existence see Sundaram [26] and Dutta and Sundaram [8,9].

[4] For example, Mirman [15] analyzes uncertainty in a model with a single controller, providing a general result about the role of uncertainty on decisions in two-period models, and discussing issues arising in the infinite-horizon setup.

[5] Our analysis does not restrict the search for optimal strategies within the linear class. Rather, it restricts attention to those dynamic games which have a symmetric equilibrium in linear Markov-perfect strategies, among all possible Markov-perfect strategies.

[6] A comprehensive analysis of how regulatory rules may affect the linkup between noncooperative strategies and the outside option for cooperation is provided by Ostrom et al. [19]. In recent work Polasky et al. [20] have built a resource game that clarifies conditions under which cooperation can become a subgame-perfect-equilibrium outcome. More interestingly, Tarui et al. [27] have extended the Polasky et al. [20] framework in order to include imperfect monitoring of each player's harvest.

[7] The Online Appendix is available at the journal's repository of supplementary material which can be accessed via http://www.jeem-supplemental.org/.