Journal of Economic Behavior & Organization 140 (2017) 91–119

Contents lists available at ScienceDirect

Journal of Economic Behavior & Organization

journal homepage: www.elsevier.com/locate/jebo

An experimental study of a common property renewable resource game in continuous time

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ARTICLE INFO

Article history:
Received 22 June 2016
Received in revised form 28 February 2017
Accepted 3 May 2017
Available online 19 May 2017

JEL classification:
C90
C73
Q20

Keywords:
Differential games
Experimental economics
Markovian strategies
Nonlinear strategies
Common property resources

ABSTRACT

Infinite time horizon linear quadratic differential games typically admit a linear Markov-perfect equilibrium as well as a continuum of equilibria with strategies that are nonlinear functions of the state variable. Using an experimental approach, we examine the empirical relevance of the nonlinear equilibriain a two-player common property resource game. We found, extraction behavior in response to evolving stock deviates significantly from the equilibrium strategies. However, long-term outcomes, in terms of steady states, predicted by both linear and nonlinear Markovian strategies are attained in significant proportions by the actual play. While 19% of participants' play resulted in a steady state that coincides with the stable steady state supported by the linear Markov-perfect equilibrium strategy, 41.5% of all games resulted in steady states within the range supported by nonlinear Markovian strategies. Our results indicate that nonlinear equilibria cannot be ruled out as irrelevant on behavioral grounds. We also found evidence for the use of simple rule-of-thumb strategies, which consist of refraining from extraction until a threshold stock is reached and extracting at a positive constant rate after the threshold is reached.

1. Introduction

Differential games are widely used to analyze strategic interactions in contexts where actions at a given moment have long-lasting repercussions. For example, oligopolistic competitions where prices do not adjust instantaneously to changes in quantity (Fershtman and Nitzan, 1991), or where investments in capacity are necessary (Driskill and McCafferty, 1989; Jun and Vives, 2004; Reynolds, 1987), or when agents face an input with reproduction constraint (Benchekroun, 2003, 2008; Colombo and Labrecciosa, 2013a,b, 2015; Mason and Polasky, 1997) represent important areas for applications of differential games.[1] The workhorse model in this literature is the linear quadratic (LQ) differential game framework, where the system of state equations is linear and the objective of each player is quadratic (Dockner et al., 2000; Haurie et al., 2012). The success of the LQ differential game framework stems from the fact that it is one of very few frameworks in

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[1] Differential games are used in several areas in economics and management, such as political economy, monetary economics, resource economics and climate change economics. Long (2010) offers a broad survey of dynamic games in economics, Jorgensen and Zaccour (2004) cover the use of differential games in management science and marketing in particular, Lambertini (2013) covers oligopolies in natural resource and environmental economics, and Jorgensen et al. (2010) review dynamic pollution games.

http://dx.doi.org/10.1016/j.jebo.2017.05.008

differential games that is analytically tractable and therefore allows to examine, in a general way, quantitative properties of an equilibrium of the differential game analyzed. There typically exists a linear subgame perfect equilibrium, and its computation is straightforward.

While the vast majority of the literature focuses on the analysis of the linear equilibria, several studies have shown that LQ differential games may admit a continuum of equilibria with strategies that are nonlinear functions of the state variable.[2] Tsutsui and Mino (1990) show that in an infinite horizon duopoly game with sticky prices, for each price between a near collusive stationary price and a competitive stationary price, there exists a stationary *local* Markov-perfect equilibrium (i.e., where strategies depend on the state variable only), which supports the price as its stationary price. In an international pollution control game, Dockner and Long (1993) show that a Pareto efficient steady state stock of pollution can correspond to the limit steady state, when the discount rate tends to zero, of Markov-perfect equilibria with nonlinear strategies. In the case of dynamic provision of a stock public good where contributions accumulate over time, Fershtman and Nitzan (1991) show that, for the linear equilibrium, the shortfall of public investment is larger than in a case where agents do not condition their contribution on the stock of public good. However, within the same public good game, Wirl (1996) examines the implications of nonlinear equilibria and shows that this result may be reversed. In a global warming game, Wirl and Dockner (1995) show that nonlinear Markovian strategies lead to Pareto inferior equilibria compared to the linear Markov-perfect equilibrium. In the case of a common property reneweable resource oligopoly, Fujiwara (2008) shows that the linear Markov-perfect equilibrium results in a higher price in the output market compared to the nonlinear Markov-perfect equilibria. Lambertini and Mantovani (2013) show that there exists a threshold number of firms beyond which resource exhaustion occurs and that this threshold is smaller under the linear strategy equilibrium than under the most cooperative nonlinear equilibrium. Colombo and Labrecciosa (2015) revisit the comparison of Bertrand versus Cournot competition in the context of a differential game where firms exploit a common property renewable asset. They show that a number of well-established results in static oligopoly theory no longer hold in a differential game oligopoly, particularly when nonlinear Markov-perfect equilibria are considered. They show that for a given steady state Bertrand equilibrium quantity, one can find a steady state Cournot equilibrium with a larger output. Moreover, in both games, when the discount rate is small enough, the collusive outcome can be sustained as a subgame perfect equilibrium.

Given the originality of the results derived for nonlinear Markov-perfect equilibria in LQ differential games, we use experiments to investigate the empirical relevance of the nonlinear equilibria in a continuous time LQ common property resource game. The goal of this paper is to determine whether nonlinear equilibria can be consistent with the observations from agents' behaviors in the experiments. One may question the relevance of the nonlinear Markov-perfect equilibria as opposed to the linear Markov-perfect equilibrium because (i) they are inherent to the continuous time games, (ii) they are much less straightforward to compute than the linear Markov-perfect equilibrium, and (iii) they are locally defined and thus are subgame-perfect only for a subset of the state space.[3] This latter point constitutes an important weakness of the locally defined nonlinear equilibria because it exogenously restrains the best reply of a player to a given region of state space. In the case of a renewable resource, for example, a player may find it profitable to drive the resource to extinction. When feasible, such strategies should be included in the set of possible replies a player might consider (see Rowat, 2007).[4]

For our investigation, we build a simple renewable resource extraction differential game that has a LQ structure for which we derive a piecewise linear Markov-perfect equilibrium and a continuum of nonlinear Markov-perfect equilibria. A renewable resource, which replenishes itself at a constant growth rate, is harvested by two firms simultaneously in continuous time. Our model is a simplified version of the productive asset oligopoly model studied by Benchekroun (2008) or Colombo and Labrecciosa (2015); it retains the competitive nature of the oligopoly; however rather than competing in an output market, the agents immediately consume the resource, they harvest. As in Dockner and Sorger (1996), each agent's instantanenous payoff depends on her extraction only.[5] In this differential game, Markovian equilibrium strategies vary in the extent of aggresivity of exploitation of the resource and therefore support infinite stable steady states, varying from the best possible steady state to very low steady states portraying the tragedy of the commons phenomena. The multiplicity of equilibria captures the idea that one player's best extraction strategy choice depends on the other player's aggressiveness in extraction. In this game, if we only focus on the Markovian strategy linear in the stock of the resource, extraction of the players reaches the best possible steady state. However, when we consider Markovian strategies nonlinear in the stock of the resource, we find many other possible steady states, including those that result from resource depletion. We implement our model in continuous time in the experimental laboratory to provide an empirical basis for human behavior in this environment.

Investigating the empirical relevance of the nonlinear equilibria in our game is an important question for at least two reasons. First, as discussed above, the outcome of equilibria with nonlinear strategies can substantially differ from the

[2] For the analysis of the existence and uniqueness of a linear subgame perfect equilibrium in LQ differential games, see Lockwood (1996). The paper does not explore the existence of nonlinear equilibria. It studies the multiplicity of linear equilibria.

[3] In contrast, the linear Markov-perfect equilibrium is global, defined over the whole state space.

[4] An alternative approach introduced by Dockner and Wagener (2014) requires a locally defined equilibrium strategy to be a global equilibrium strategy of subgames where the controls are constrained in such a way that no player can drive the state out the domain of definition.

[5] In Dockner and Sorger (1996), agents face a constraint on their maximum harvest, and the model is not LQ: the instantaneous utility is the square root function and the reproduction function of the asset is quite general (twice continuously differentiable, strictly concave, and inverted U-shaped).