15 Resource Economics

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Contents

Abstract

This chapter provides a selective survey of dynamic game models of exploitation of natural resources. It covers both renewable resources and exhaustible resources. In relation to earlier surveys (Long, A survey of dynamic games in economics, World Scientific, Singapore, 2010; Long, Dyn Games Appl 1(1):115–148, 2011), the present work includes many references to new developments that appeared after January 2011 and additional suggestions for future research. Moreover, there is a greater emphasis on intuitive explanation.

Keywords

Exhaustible resources · Renewable resources · Overexploitation · Market structure · Dynamic games

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1 Introduction

Natural resources play an important role in economic activities. Many resources are essential inputs in production. Moreover, according to the World Trade Report of the WTO (2010, p. 40), "natural resources represent a significant and growing share of world trade and amounted to some 24 per cent of total merchandise trade in 2008." The importance of natural resources was acknowledged by classical economists. Smith (1776) points out that the desire to possess more natural resources was one of the motives behind the European conquest of the New World and the establishment of colonies around the globe. Throughout human history, many conflicts between nations or between social classes within a nation (e.g., the "elite" versus the "citizens") are attributable to attempts of possession or expropriation of natural resources (Long 1975; van der Ploeg 2010). Many renewable resources are at risk because of overexploitation. For example, in the case of fishery, according to the Food and Agriculture Organization, in 2007, 80 % of stocks are fished at or beyond their maximum sustainable yield (FAO 2009). Recent empirical work by McWhinnie (2009) found that shared fish stocks are indeed more prone to overexploitation, confirming the theoretical prediction that an increase in the number of agents that exploit a resource will reduce the equilibrium stock level.

Some natural resources, such as gold, silver, oil, and natural gas, are nonrenewable. They are sometimes called "exhaustible resources." Other resources, such as fish and forest, are renewable. Water is renewable in regions with adequate rainfall, but certain aquifers can be considered as nonrenewable, because the rate of recharge is very slow.[1] Conflicts often arise because of lack of well-defined property rights in the extraction of resources. In fact, the word "rivals" was derived from the Latin word "rivales" which designated people who drew water from the same stream (rivus).[2] Couttenier and Soubeyran (2014, 2015) found that natural resources are often causes of civil conflicts and documented the empirical relationship between water shortage on civil wars in sub-Saharan Africa.

Economists emphasize an essential feature of natural resource exploitation: the rates of change in their stocks are influenced by human action. In situations where the number of key players is not too large, the appropriate way of analyzing the rivalrous exploitation of natural resources is to formulate a dynamic game. This chapter provides a selective survey of dynamic game models of exploitation of natural resources. In relation to earlier surveys (Long 2010, 2011), the present work

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[1] For a review of the game theoretic approach to water resources, see Dinar and Hogarth (2015). For some recent models of differential games involving water transfer between two countries, see Cabo et al. (2014) and in particular Cabo and Tidball (2016) where countries cooperate in the infrastructure investment stage but play a noncooperative game of water transfer in a second stage. Cabo and Tidball (2016) design a time-consistent imputation distribution procedure to ensure cooperation, along the lines of Jørgensen and Zaccour (2001).

[2] Dictionnaire LE ROBERT, Société du Nouveau Littré, Paris: 1979.

includes many references to new developments that appeared since 2011. Moreover, this chapter places a greater emphasis on intuitive explanation.

The next section reviews critical issues and dynamic game models in the exploitation of renewable resources. Section 3 is devoted to exhaustible resources. The final section offers some thoughts on future directions of research.

2 Renewable Resources

Renewable resources are natural resources for which a positive steady-state stock level can be maintained while exploitation can remain at a positive level for ever. Some examples of renewable resources are forests, aquifers, fish stocks, and other animal species. Without careful management, some renewable resources may become extinct. The problem of overexploitation of natural resources is known as the "Tragedy of the commons" (Hardin 1968).[3] There is a large literature on the dynamic tragedy of the commons. While some papers focus on the case where players use open-loop strategies (e.g., Clark and Munro 1975; Kemp and Long 1984; Kaitala et al. 1985; Long and McWhinnie 2012), most papers assume that players use feedback strategies (e.g., Dinar and Zaccour 2013; Long and Sorger 2006). In what follows, we review both approaches.[4]

2.1 The Tragedy of the Commons: Exploitation of Renewable Natural Assets

The standard fishery model is Clark and Munro (1975). There are m fishermen who have access to a common fish stock, denoted by $S(t) \geq 0$. The quantity of fish that fisherman i harvests at time t is $h_i(t) = \gamma L_i(t)S(t)$ where $L_i(t)$ is his effort and γ is called the catchability coefficient. In the absence of human exploitation, the natural rate of reproduction of the fish stock is $dS/dt = G(S(t))$, where it is assumed that $G(S)$ is a hump-shaped and strictly concave function, with $G(0) = 0$ and $G'(0) > 0$. Taking into account the harvests, the transition equation for the stock is

$$\frac{dS}{dt} = G(S(t)) - \sum_{i=1}^{m} \gamma L_i(t)S(t)$$

By assumption, there exists a unique stock level S_M such that $G'(S_M) = 0$. The stock level S_M is called the maximum sustainable yield stock level. The quantity

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[3] However, as pointed out by Ostrom (1990), in some societies, thanks to good institutions, the commons are efficiently managed.

[4] See Fudenberg and Tirole (1991) on the comparison of the concepts of open-loop equilibrium and feedback or Markov-perfect equilibrium.

$G(S_M)$ is called the maximum sustainable yield.[5] A common functional form for $G(S)$ is $rS(1 - S/K)$ where r and K are positive parameters. The parameter r is called the intrinsic growth rate, and K is called the carrying capacity, because when the stock S is greater than the carrying capacity level K, the fish population declines.

2.1.1 Open-Loop Games of Fishery

Clark and Munro (1975) propose an open-loop differential game of exploiting a common access fish stock. For simplicity, assume that the market price of fish, P, is exogenous and constant over time. The total effort cost of fisherman i at time t is $cL_i(t)$, where c is a positive parameter, assumed to be small relative to P. Assume that L_i must belong to the interval $\left[0, \overline{L}\right]$ where $\overline{L}$ is player i's maximum possible effort level. Each fisherman i chooses a time path $L_i(t) \in \left[0, \overline{L}\right]$ to maximize the integral of his discounted stream of profit,

$$J_i = \int_0^{\infty} e^{-\rho t} \left[p\gamma L_i(t)S(t) - cL_i(t)\right] dt$$

where $\rho > 0$ is the discount rate, while taking into account the transition equation

$$\dot{S}(t) = G(S) - \gamma L_i(t)S(t) - \gamma \sum_{j \neq i} L_j(t)S(t)$$

If the fishermen were able and willing to cooperate, they would coordinate their efforts, and it is easy to show that this would result in a socially efficient steady-state stock, denoted by S_{∞}^E, which satisfies the following equation[6]:

$$\rho = G'(S_{\infty}^E) + \frac{G(S_{\infty}^E)}{S_{\infty}^E} \left[\frac{c}{P\gamma S_{\infty}^E - c}\right] \tag{15.1}$$

The intuition behind this equation is as follows. The left-hand side is the market rate of interest which producers use to discount the future profits. The right-hand side is the net rate of return of leaving a marginal fish in the pool instead of catching it. It is the sum of two terms: the first term, $G'(S_{\infty}^E)$, is the marginal natural growth rate of the stock (the biological rate of interest), and the second term is the gain that results from the reduction (brought about by a marginal increase in stock level) in the required aggregate effort to achieve the steady-state catch level. In an efficient solution, the two rates of return must be equalized, for otherwise further gains would be achievable by arbitrage.

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[5] It has been estimated that about 80 % of fish stocks are exploited at or beyond their maximum sustainable yields. See FAO (2009).

[6] We assume that the upper bound constraint on effort is not binding at the steady state.

What happens if agents do not cooperate? Clark and Munro (1975) focus on the open-loop Nash equilibrium, i.e., each agent i determines her own time path of effort and takes the time path of efforts of other agents as given. Agent i believes that all agents $j \neq i$ are pre-committed to their time paths of effort $L_j(t)$, regardless of what may happen to the time path of the fish stock when i deviates from her plan. Assuming that $\overline{L}$ is sufficiently large, it can be shown that the open-loop Nash equilibrium results in a steady-state stock S_∞^{OL} that satisfies the equation

$$\rho = G'(S_\infty^{OL}) + \frac{1}{m}\frac{G(S_\infty^{OL})}{S_\infty^{OL}}\left[\frac{c}{P\gamma S_\infty^{OL} - c} - (m-1)\right] \tag{15.2}$$

The steady-state stock S_∞^{OL} is socially inefficient. It is equal to the socially efficient stock level S_∞^{E} only if $m = 1$. This inefficiency result is a consequence of a *dynamic overcrowding production externality*: when a fisherman catches more fish today, this will reduce level of tomorrow's stock of fish, which increases tomorrow's effort cost of all fishermen at any intended harvest level.[7]

A weakness of the concept of open-loop Nash equilibrium is that it assumes that players do not use any information acquired during the game and consequently do not respond to deviations that affect the anticipated path of the stock. Commenting on this property, Clemhout and Wan (1991) write: "for resource games at least, the open-loop solution is neither an equally acceptable alternative to the closed loop solution nor a safe approximation to it." For this reason, we now turn to models that focus on closed-loop (or feedback) solution.

2.1.2 Feedback Games of Exploitation of Renewable Natural Assets

The simplest fishery model where agents use feedback strategies is the Great Fish War model of Levhari and Mirman (1980). We present below a slightly modified version of that model. Thanks to the assumed special functional forms (logarithmic utility functions and a net reproduction function that is log-linear), it is possible to derive a closed-form solution of the equilibrium harvesting strategies. However, the essence of the results of Levhari and Mirman (1980) can be preserved under more general functional specifications (e.g., Dutta and Sundaram 1993b).

The model is formulated in discrete time. Consider the case of n identical countries that have common access to a fish stock S_t. Let h_{it} denote country i's harvest in period t. Define the total harvest in period t by $H_t = \sum_{i=1}^{n} h_{it}$. (We will show that $H_t \leq S_t$ in equilibrium.) Assume that the next period's fish stock is given by the difference equation $S_{t+1} = (S_t - H_t)^{\kappa}$ where $0 < \kappa < 1$. The parameter κ may be regarded as an index of the future availability of the resource. An increase in κ represents a low future availability.

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[7] If the amount harvested depends only on the effort level and not on the level of the stock, i.e., $h_i = \gamma L_i$, then in an open-loop equilibrium, there is no dynamic overcrowding production externality. In that case, it is possible that open-loop exploitation is Pareto efficient; see Chiarella et al. (1984).

Harvesting is costless, and the utility of consuming h_{it} is $\sigma \ln h_{it}$, where $\sigma > 0$ is a parameter which is interpreted as the quality of the resource. For the moment, assume $\sigma = 1$. Let β denote the discount factor, where $0 < \beta < 1$. The payoff to country i is $\sum_{t=0}^{\infty} \beta^t \ln h_{it}$. It is simple to verify that if the countries cooperate, the optimal common feedback policy is $h_{it}^C(S_t) = (1 - \beta\kappa)S_t n^{-1}$. The resulting cooperative steady-state stock is $S_\infty = (\beta\kappa)^{\kappa/(1-\kappa)}$.

Turning to the noncooperative game, the Bellman equation for country i is

$$V_i(S) = \max_{h_i} \{\ln(h_i) + \beta V_i((S - H_{-i} - h_i)^\kappa)\}$$

where $H_{-i} = H - h_i$. Levhari and Mirman find that there exists a Markov-perfect Nash equilibrium in which countries use the linear feedback strategy

$$h_{it}^M(S_t) = \frac{1 - \beta\kappa}{n - \beta\kappa(n-1)} S$$

Thus, at each level of the stock, the noncooperative harvest rate exceeds the cooperative one. The resulting steady-state stock level is lower.

The Levhari-Mirman result of overexploitation confirms the general presumption that common access leads to inefficient outcome. The intuition is simple: if each player believes that the unit it chooses not to harvest today will be in part harvested by other players tomorrow, then no player will have a strong incentive to conserve the resource. This result was also found by Clemhout and Wan (1985), who used a continuous-time formulation. The Levhari-Mirman overexploitation result has been extended to the case of a coalitional fish war (Breton and Keoula 2012; Kwon 2006), using the same functional forms for the utility function and the net reproduction function. Kwon (2006) assumes that there are n ex ante identical countries, and m of them form a coalition, so that the number of players is $\eta = n - m + 1$. A coalition is called profitable if the payoff of a coalition member is greater than what it would obtain in the absence of the coalition. The coalitional Great Fish War game is the game involving a coalition and the $n - m$ outsiders. A coalition is said to be stable under Nash conjectures (as defined in d'Aspremont et al. 1983) if two "stability conditions" are satisfied. First is internal stability, which means that if a member drops out of the coalition, assuming that the other $m - 1$ members stay put, it will obtain a lower payoff. Second is external stability, which means that if an outsider joins the coalition, assuming that the existing m members will continue their membership, its payoff will be lower than its status quo payoff. Kwon (2006) shows that the only stable coalition (under the Nash conjectures) is of size two. Thus, when n is large, the overexploitation is not significantly mitigated when such a small stable coalition is formed. Breton and Keoula (2012) investigate a coalitional war model that departs from the Nash conjectures: they replace the Nash conjectures with what they call "rational conjectures," which relies on the farsightedness assumption. As they aptly put it, "the farsightedness assumption in a coalitional game acknowledges the fact that a deviation from a single player will lead to the formation of another coalition structure, as the result of possibly successive moves of her rivals in order to improve their payoff" (p. 298).[8] Breton and Keoula (2012) find that under plausible values of parameters, there is a wide scope for cooperation under the farsightedness assumption. For example, with $n = 20$, $\beta = 0.95$, and $\kappa = 0.82$, a coalition of size $m = 18$ is farsightedly stable (p. 305).

Fesselmeyer and Santugini (2013) extend the Levhari-Mirman fish war model to the case where there are exogenous environmental risks concerning quality and availability.[9] The risks are modeled as follows. Let x_t denote the "state of the environment" at date t. Assume that x_t can take on one of two values in the set $\{1, 2\}$. If $x_t = 1$, then the probability that $x_{t+1} = 2$ is ρ, where $0 < \rho < 1$, and the probability that $x_{t+1} = 1$ is $1 - \rho$. If $x_t = 2$, then $x_{t+1} = 2$ with probability 1. Assume that $x_0 = 1$. Then, since $\rho > 0$, there will be an environmental change at some time in the future. The authors find that if there is the risk that an environmental change (an increase in x_t from 1 to 2) will lead to lower renewability (i.e., $\kappa_2 \geq \kappa_1$), then rivalrous agents tend to reduce their exposure to this risk by harvesting less, as would the social planner; however, the risk worsens the tragedy of the commons in the sense that, at any given stock level, the ratio of Markov-perfect Nash equilibrium exploitation to the socially optimal harvest increases. In contrast, when the only risk is a possible deterioration in the quality of the fish (i.e., $\sigma_2 < \sigma_1$), this tends to mitigate the tragedy of the commons.

Other discrete-time models of dynamic games on renewable natural assets include Amir (1989) and Sundaram (1989), where some existence theorems are provided. Sundaram's model is a generalization of the model of Levhari and Mirman (1980): Sundaram replaces the utility function $\ln h_i$ with a more general strictly concave function $u(h_i)$ with $u'(0) = \infty$, and the transition function $S_{t+1} = (S_t - H_t)^\kappa$ is replaced by $S_{t+1} = f(S_t - H_t)$ where $f(0) = 0$ and $f(.)$ is continuous, strictly increasing, and crosses the 45 degree line exactly once. Assuming that all players are identical, Sundaram (1989) proves that there exists a Markov-perfect Nash equilibrium (MPNE) in which all players use the same strategy. Another result is that along any equilibrium path where players use stationary strategies, the time path of the stock is monotone. Sundaram (1989) also shows that in any symmetric Markov-perfect Nash equilibrium, the MPNE stationary strategy cannot be the same as the cooperative harvesting strategy $h^C(S)$.

Dutta and Sundaram (1993a) provide a further generalization of the model of Levhari and Mirman (1980). They allow the period payoff function to be dependent on the stock S in an additively separable way: $U_i(h_i, S) = u_i(h_i) + w(S)$ where $w(.)$ is continuous and increasing. For example, if the resource stock is a forest, consumers derive not only utility $u_i(h_i)$ from using the harvested timber but also

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[8] The farsightedness concept was formalized in Greenberg (1990) and Chwe (1994) and has been applied to the literature on public goods (Ray and Vohra 2001) and international environmental agreements (de Zeeuw 2008; Diamantoudi and Sartzetakis 2015).

[9] For ownership risks, see Bohn and Deacon (2000).

pleasure $w(S)$ when they hike in a large forested area or when a larger forest ensure greater biodiversity than a smaller one. They show that a cooperative equilibrium exists. For a game with only three periods, they construct an example in which there is no Markov-perfect Nash equilibrium, if one player's utility is linear in consumption while his opponent has a strictly concave utility function. When the function $w(S)$ is *strictly convex*, they show by example that the dynamics of the stock along an equilibrium path can be very irregular. One may argue that in some contexts, the strict convexity of $w(S)$ (within a certain range) may be a plausible assumption. For example, within a certain range, as the size of a forest doubles, biodiversity may triple.[10] Finally, they consider the case of an infinite horizon game with a zero rate of discount. In this case, they assume that each player cares only about the long-run average (LRA) payoff, so that the utilities that accrue in the present (or over any finite time interval) do not count. For example, a "player" may be a government of a country in which the majority of voters adhere to Sidgwick's view that it is immoral to discount the welfare of the future generations (Sidgwick 1874). With zero discounting, the LRA criterion is consistent with the axiom that social choice should display "non-dictatorship of the present" (Chichilnisky 1996). Under the LRA criterion, Dutta and Sundaram (1993a) define the "tragedy" of the commons as the situation where the stock converges to a level lower than the golden rule stock level. They show that under the LRA criterion, there exists an MPNE that does not exhibit this "tragedy" property. This result is not very surprising, because, unlike the formulation of Clark and Munro (1975) where harvest depends on the product of effort and stock, $\gamma L_i(t)S(t)$, the model of Dutta and Sundaram assumes that the stock has no effect on the marginal product of labor, and thus, the only incentive to grab excessively comes from the wish to grab earlier than one's rivals, and this incentive may disappear under the LRA criterion, as the present consumption levels do not count.[11] However, whether a tragedy occurs or not, it can be shown that any MPNE is suboptimal from any initial state.[12] It follows that, in a broad sense, the tragedy of the commons is a very robust result.

While the model of Levhari and Mirman (1980) shows that the Markov-perfect equilibrium is generically not Pareto efficient, inefficiency need not hold at every initial stock level. In fact, Dockner and Sorger (1996) provide an example of a fishery model in which there is a continuum of Markov-perfect equilibria, and they show that in the limit, as the discount rate approaches zero, the MPNE stationary

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[10] In contrast, in the standard models, where all utility functions are concave, it can be shown that the equilibrium trajectory of the state variable must eventually become monotone. See Dutta and Sundaram (1993b).

[11] Sundaram and Dutta (1993b) extend this "no tragedy" result to the case with mild discounting: as long as the discount rate is low enough, if players use *discontinuous* strategies that threaten to make a drastic increase in consumption when the stock falls below a certain level, they may be able to lock each other into a stock level that is dynamically inefficient and greater than the cooperative steady state.

[12] Except possibly the cooperative steady state (Dutta and Sundaram 1993b, Theorem 3).

steady-state stock converges to the steady-state stock of the (efficient) cooperative solution. This result is of course a local result. It does not imply that the MPNE harvesting rule coincides with the socially optimal one, for all stock levels. A special feature of Dockner and Sorger (1996) model is that they assume a square root utility function. The reproduction function for the stock x is $F(x)$, a strictly concave, hump-shaped function, with $F(0) = F(1) = 0$. There is a constant, exogenous upper bound $\overline{u}$ on harvest rates that is independent of the stock level. They show that the cooperative solution is unique and leads to the steady-state stock $x_1 \in (0, 1)$, where the effect of the stock on the rate of reproduction, $F'(x_1)$, is equal to the discount rate r, a familiar result (Long 1977). In contrast, when two players behave noncooperatively, Dockner and Sorger (1996) show that there is a continuum of symmetric equilibria, which differ from each other in terms of the interval of stock levels such that both players harvest at the maximum rate $\overline{u}$. For each of these equilibria, the harvesting rate when $u < \overline{u}$ is found to be an increasing function of the discount rate r. The intuition behind the multiplicity of equilibria is simple: if one player believes that the other exploits at the maximum rate over a given interval of stock, then she has no incentive to conserve the stock, and thus its best response is to do likewise. Therefore, there is a continuum of intervals of stock with maximum exploitation. The corresponding Markov-perfect exploitation strategy displays a jump discontinuity at the lower bound of each such interval.[13] An interesting property of the model is that as the rate of discount tends to zero, the steady state of the noncooperative common access game coincides with the steady state of the cooperative game.[14] This result is in sharp contrast with Levhari and Mirman (1980), where the tragedy of the commons does not vanish when the discount rate becomes arbitrarily small. This discrepancy can be attributed to two factors. First, there is no exogenous upper bound on harvests in Levhari and Mirman (1980). Second, the discrete-time formulation of the net reproduction function in Levhari and Mirman (1980) is quite different from the continuous-time formulation in Dockner and Sorger (1996), as the discrete-time formulation implies that agents are able to make some short-term commitment to their intended harvest levels.[15] While there may exist many MPNEs, some of which can be discontinuous, it can be shown that there exists a class of utility functions that yield MPNE strategies that are linear in the stock, provided that the resource growth function has parameters that are suitably related to the parameters of the utility function. See Gaudet and Lohoues (2008) and Long (2011). For existence theorems on MPNEs in resource exploitation games, see Amir (1987, 1987).

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[13] Dockner and Sorger (1996), Lemma 1.

[14] Dockner and Long (1993) find similar results in a pollution game.

[15] Efficiency can also be ensured if players can resort to trigger strategies, see Cave (1987) and Benhabib and Radner (1992), or if there exist countervailing externalities, as in Martin-Herrán G, Rincón-Zapareto J (2005).

2.2 Renewable Resource Exploitation Under Oligopoly

While most models of renewable resource extraction assume price-taking behavior, there has been a recent increase in interest on the implications of oligopolistic behavior for renewable resources. Most authors rely on specific demand functions in order to derive closed-form solutions (Benchekroun 2008; Dockner et al. 1989; Fujiwara 2011; Jørgensen and Yeung 1996). Jørgensen and Yeung (1996) assume that the demand function is of the form $P = 1/\sqrt{H}$where H is the aggregate harvest while the cost of harvesting h_i is $ch_i/\sqrt{S}$ where S is the resource stock. Combining with a square root function for the resource growth rate, the model yields MPNE strategies that are linear in the stock. Long (2011) provides a generalization of the model. More recent contributions discuss the role of property rights (Colombo and Labrecciosa 2013a,b), Bertrand rivalry versus Cournot rivalry (Colombo and Labrecciosa 2015), the role of nonlinear strategies (Colombo and Labrecciosa 2015; Lambertini and Mantovani 2014), and the impact of market integration in an international trade framework (Fujiwara 2011).

Benchekroun (2008) assumes the linear demand function $P = A - BH$, with an arbitrary number of firms. To derive closed-form value functions, he approximates the logistic growth function with a tent-shaped function. The slope of the tent at the zero stock level is called the inherent growth rate of the resource. He finds that there exists an MPNE where fishing firms use a piecewise linear strategy: when the stock is small, firms do not harvest at all, until a threshold level of stock is reached. Beyond that threshold, the equilibrium harvesting rate is linear in the stock, until an upper threshold stock level is reached. For stock levels higher than this upper threshold, firms behave as if they had no concern for the stock dynamics. Myopia becomes individually optimal in this range. Benchekroun (2008) obtains a number of interesting results. First, an increase in the inherent growth rate of the resource may result in a lower steady-state stock. This is similar to the voracity effect discussed in Tornell and Lane (1999). Second, reducing the number of oligopolists can lead to higher steady-state output of the industry, in contrast to the results of the model of oligopoly without a resource stock. This result, at first surprising, can be explained by Solow's idea that a monopolist is the conservationist's best friend.

Benchekroun's 2008 model of oligopolistic exploitation of a renewable resource has been modified and extended in several directions, to examine a number of related issues, such as asymmetry among firms (Benchekroun et al. 2014) and mergers (Benchekroun and Gaudet 2015). In Benchekroun et al. (2014), it is found that the simple piecewise linear strategies in Benchekroun (2008) cannot survive a small departure from the symmetric cost assumption. In Benchekroun and Gaudet (2015), the authors show that there exists an interval of asset stock size such that when the common property stock is inside that interval, any merger is profitable, contrary to the standard static model of merger which asserts that any merger involving less than 80 % of the industry will be unprofitable (Salant et al. 1983). Intuitively, the difference is due to the role of the resource stock (an asset) which constraint cumulative output in a resource oligopoly, while in the standard model of Salant et al. (1983), production is not constrained by assets.

2.3 The Effects of Status Concern on the Exploitation of Renewable Resources

While the standard economic theory emphasizes rationality leading to profit maximization and maximization of the utility of consumption, it is well known that there are other psychological factors that are also driving forces behind our actions.[16] Perceptive economists such as Veblen (1899) and noneconomists, such as Kahneman and Tversky (1984), have stressed these factors. Unfortunately, the "Standard Model of Economic Behavior" does not take into account psychological factors such as emulation, envy, status concerns, and so on. Fortunately, in the past two decades, there has been a growing economic literature that examines the implications of relaxing the standard economic assumptions on preferences (see, e.g., Frey and Stutzer 2007).

The utility that an economic agent derives from her consumption, income, or wealth tends to be affected by how these compare to other economic agents' consumption, income, or wealth. The impact of status concern on resource exploitation has recently been investigated in the natural resource literature. Alvarez-Cuadrado and Long (2011) model status concern by assuming that the utility function of the representative individual depends not only on her own level of consumption c_i and effort L_i but also on the average consumption level in the economy, C, such that $u_i = U(c_i, C, L_i)$. This specification captures the intuition that lies behind the growing body of empirical evidence that places interpersonal comparisons as a key determinant of individual well-being. Denote the marginal utility of own consumption, average consumption, and effort by U_1, U_2, and U_L, respectively. The level of utility achieved by the representative individual is increasing in her own consumption but at a decreasing rate, $U_1 > 0$ and $U_{11} < 0$, and decreasing in effort, $U_L < 0$. In addition, it is assumed that the utility function is jointly concave in individual consumption and effort with $U_{1L} \leq 0$, so the marginal utility of consumption decreases with effort. Under this fairly general specification, Alvarez-Cuadrado and Long (2011) show that relative consumption concerns can cause agents to overexploit renewable resources even when these are private properties. Situations where status-conscious agents exploiting a common pool resource behave strategically are analyzed in Long and Wang (2009), Katayama and Long (2010), and Long and McWhinnie (2012).

Long and McWhinnie (2012) consider a finite number of agents playing a Cournot dynamic fishery game, taking into account the effect of the fishing effort of other agents on the evolution of the stock. In other words, they are dealing with a differential game of fishery with status concerns. Long and McWhinnie (2012) show that the overharvesting associated with the standard tragedy of the commons problem becomes intensified by the desire for higher relative performance, leading to a smaller steady-state fish stock and smaller steady-state profit for all the fishermen. This result is quite robust with respect to the way status is modeled.

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[16] See e.g. Fudenberg and Levine (2006, 2012).

The authors consider two alternative specifications of relative performance. In the first specification, relative performance is equated to relative after-tax profits. In the second specification, it is relative harvests that matter. The authors examine a tax package (consisting of a tax on relative profit and a tax on effort) and an individual quota as alternative policy tools to implement the socially efficient equilibrium.

The analysis of Long and McWhinnie (2012) relies on two key assumptions: first, each agent takes as given the time paths of resource exploitation of other agents (i.e., the authors restrict attention to open-loop strategies), and second, the agents take the market price of the extracted resource as given (i.e., the goods markets are perfectly competitive). Those assumptions have been relaxed by Benchekroun and Long (2016). Interestingly, they show that when agents use feedback strategies and the transition phase is taken into account, the well-established result that status concern exacerbates the tragedy of the commons must be seriously qualified. More specifically, when agents are concerned about their relative profit, the authors find that there exists an interval of the stock size of the resource for which the extraction policy under status concern is less aggressive than the extraction policy in the absence of status concern.

2.4 Regime-Switching Strategies and Resource Exploitation

Rivalry in the exploitation of common property resources can motivate players to take additional action (other than the choice of the rates of extraction) in order to get an upper hand. The enclosure of the commons is one way of affecting a regime change (Smith 1776, Book 1, Chap. 11), though it may lead to a loss of social welfare when the enclosing costs are high (Long 1994). As Long (1994) points out, the party that encloses the commons is affecting the other parties' production sets (their ability to transform their labor into food). This is itself a kind of externalities that might be more severe than the overcrowding externalities.

Crabbé and Long (1993) study a fishery game where a dominant player deters entry of poachers by creating excessive overcrowding, driving their profits to zero. Tornell (1997) models the game between two infinitely lived agents who fight over the choice over property rights regime: sharing versus exclusive ownership. He shows that a potential equilibrium of the game involves multiple switching between regimes. Thus Tornell's model sheds light on the political instability of some resource-rich economies.

Long et al. (2014) model the choice of switching from one exploitation technology to another when two infinitely lived agents with different costs of technology adoption have common access to a resource stock. They find that the player with low investment cost is the first player to adopt a new harvesting technology. She faces two countervailing incentives: on the one hand, an early switch to a more efficient technology enables her to exploit the resources more cheaply; on the other hand, by inducing the regime change, which tends to result in a faster depletion, she might give her opponent an incentive to hasten the date of his technology adoption, if the opponent investment cost decreases as the stock decreases. As a consequence, in a Markov-perfect equilibrium, the balance of these strategic considerations may make the low-cost player delay technology adoption even if her fixed cost of adoption is zero, contrary to what she would do (namely, immediate adoption) if she were the sole player.

3 Exhaustible Resources

Exhaustible resources (also called nonrenewable resources) are resources for which the rate of change of the *individual* stocks is never positive (even though the *aggregate* stock may increase through discovery of additional stocks). In the simplest formulation, the transition equation for an exhaustible resource stock S is

$$\frac{dS}{dt} = -\sum_{i=1}^{m} E_i(t), \text{ with } S(0) = S_0 > 0$$

where $E_i(t) \geq 0$ denotes the extraction rate of player i. If $m = 1$, the stock is extracted by a single firm. In the case of a shared resource stock, we have $m \geq 2$. There are two different meanings of resource exhaustion. Physical exhaustion means that extractions continue until the stock becomes zero at some finite time T (or possibly asymptotically). In contrast, economic exhaustion means that at some stage, the firm finds it optimal to abandon the stock because the extraction cost becomes too high, even though extraction is still feasible. Depending on the types of questions the researcher is asking, one formulation of exhaustion may be more appropriate than the other.[17] In the case of eventual physical exhaustion, it is most transparent that the opportunity cost of extracting one more unit of the resource this period is the foregone marginal profit next period as that unit would no longer be available for extraction in the next period. Thus, intertemporal arbitrage implies that along an *equilibrium* extraction path, the discounted marginal profits from extraction must be the same between any two adjacent periods. This is known as the Hotelling Rule.[18] Observed extraction paths are not necessarily equilibrium paths because of unanticipated supply shocks or demand shocks. In fact, models of dynamic games involving exhaustible resources were developed after the unanticipated quadrupling in the world price of petroleum between late 1973 and early 1974, “engineered by the newly assertive Organization of Petroleum Exporting Countries (OPEC), an international cartel that includes most large oil producers” (Krugman et al. 2015, p. 572). Not surprisingly, a major emphasis of this literature is on cartel and oligopolies.

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[17] See Salo and Tahvonen (2001) for the modeling of economic exhaustion in a duopoly.

[18] See Gaudet (2007) for the theory and empirics related to the Hotelling Rule.

3.1 Exhaustible Resource Extraction Under Different Market Structures

Salant (1976) considers an open-loop game between an exhaustible resource cartel and a competitive fringe, under Nash-Cournot behavior: the cartel takes the time path of extraction of the fringe as given and determines its own time path, knowing that it can influence the market price. Salant finds that the formation of a cartel raises the profits of its members, compared to the case where all firms are price takers. However, nonmembers gain more than cartel members. This result suggests that an exhaustible resource cartel is likely to face defection or cheating by its members. This might well explain the instability of oil prices in the recent history. Ulph and Folie (1980) extend Salant's model to allow for differences in marginal costs. Gilbert (1978) considers instead the case where the cartel is an open-loop Stackelberg leader: it announces to the fringe its time path of future output before the fringe firms make their output decision. However, it can be shown that an open-loop Stackelberg equilibrium is time inconsistent: at a later stage, if the cartel can renege on its preannounced path, it will find it profitable to do so.[19] Benchekroun and Withagen (2012) provide a theoretical justification for the price-taking behavior of the fringe.

To overcome the time-inconsistency problem, Groot et al. (2003) propose a feedback Stackelberg formulation. This formulation assumes that each fringe firm believes its value function to be a linear function of its stock, with a constant slope, which it takes as given. However, this slope is not given: it is in fact influenced by the cartel's extraction policy.

An alternative market structure is oligopoly. Loury (1986) studies a model of oil oligopolists that use open-loop strategies.[20] He finds that under identical and constant extraction costs, smaller firms exhaust their stocks before larger ones and that industry production maximizes a weighted average of profits and consumers' welfare. Benchekroun et al. (2009, 2010) find that under open-loop oligopoly, firms with different costs may produce at the same time, and additional stocks of the resource can result in a lower social welfare. The latter result has a counterpart in the theory of static oligopoly: a small reduction in the marginal cost of higher cost firms may reduce welfare (Lahiri and Ono 1988; Long and Soubeyran 2001). It is also related to Gaudet and Long (1994), who find that a marginal redistribution of resource stocks between two oligopolists to make their reserves more unequal can increase the industry's profit. Models of oligopoly with feedback extraction strategies include Salo and Tahvonen (2001) and Benchekroun and Long (2006). The latter paper shows that a windfall gain (a stock discovery) can be harmful to firms in a nonrenewable resource oligopoly.

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[19] For a proof of the time inconsistency of open-loop Stackelberg equilibrium, see, for example, Dockner et al. (2000), or Long (2010).

[20] See also Lewis and Schmalensee (1980).

3.2 Dynamic Resource Games Between Countries

The world markets for gas and oils consist mainly of a small number of large sellers and buyers. For instance, the US Energy Information Administration reports that the major energy exporters concentrate on the Middle East and Russia, whereas the United States, Japan, and China have a substantial share in the imports. These data suggest that bilateral monopoly roughly prevails in the oil market in which both parties exercise market power. What are the implications of market power for welfare of importing and exporting countries and the world?

Kemp and Long (1979) consider an asymmetric two-country world. They assume that the resource-rich economy can only extract the resource, while the resource-poor economy imports the resource as an input in the production of the consumption goods. They study the implications of market power in the resource market by comparing a competitive equilibrium path of extraction and final good production with the outcome under two scenarios where market power is exercised by only one of the countries. If the resource-rich country is aggressive, it will set a time path of oil price so that the marginal revenue from oil exports rises a rate equal to the endogenously determined rate of interest. In the special case where the production function of the final good is Cobb-Douglas, the resource-rich country is not better off relative to the competitive equilibrium.[21] If the resource-poor country is aggressive, it will set a specific tariff path that makes oil producers's price equal to extraction cost, thus effectively appropriating all the resource rents. Kemp and Long (1979) point out that this result will be attenuated if the resource-rich country can also produce the consumption good.[22] Bergstrom (1982) considers a model with many resource-importing countries. He assumes that the international market is integrated so that all importing countries pay the same price for the resource. He shows that if the resource-poor countries can commit to a time-invariant ad valorem tariff rate on oil, they can extract a sizable gain at the expense of resource-rich economies.

Kemp and Long (1980) present a three-country model where there is a dominant resource-poor economy that acts as an open-loop Stackelberg leader in announcing a time path of per-unit tariff rate, while the resource-rich country and the rest of the world are passive. They show that such a time path is time inconsistent, because at a later stage, having been able to induce the resource-rich country to supply more earlier on, the leader will have an incentive to reduce the tariff rate so as to capture a larger share of the world's oil imports.[23]

Karp and Newbery (1992) numerically compute time-consistent tariff policies in a game where several resource-poor economies noncooperatively impose tariffs

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[21] This corresponds to the result that, in a closed economy, the market power of an oil monopolist with zero extraction cost disappears when the elasticity of demand is constant. See, e.g., Stiglitz (1976).

[22] This is confirmed in Brander and Djajic (1983), who consider a two-country world in which both countries use oil to produce a consumption good, but only one of them is endowed with oil.

[23] See also Karp (1984) and Maskin and Newbery (1990) for the time-inconsistency issue.

on oil. Assuming that oil producers are price takers and plan their future outputs according to some Markovian price-expectation rule, the authors report their numerical results that is possible for oil-importing countries to be worse off relative to the free trade case. In a different paper, Karp and Newbery (1991) consider two different orders of move in each infinitesimal time period. In their importer-move-first model, they assume that two importing countries noncooperatively choose the quantity to be imported. In the exporter-move-first model, the competitive exporting firms choose how much to export before they know the tariff rates for the period. The authors report their numerical findings that for small values of the initial resource stock, the importer-move-first model yields lower welfare for the importers compared to the exporter-move-first model.

Rubio and Estriche (2001) consider a two-country model where a resource-importing country can tax the polluting fossil fuels imported from the resource-exporting country. Revisiting that model, Liski and Tahvonen (2004) show that there are two incentives for the resource-importing country to intervene in the trade: taxing the imports of fossil fuels serves to improve the importing country's terms of trade, while imposing a carbon tax is the Pigouvian response to climate-change externalities. They show that the gap between the price received by fossil-fuel exporters and the price faced by consumers in the importing country can be decomposed into two components, reflecting the terms-of-trade motive and the Pigouvian motive.

Chou and Long (2009) set up a model with three countries: two resource-importing countries set tariff rates on imported oil, and a resource-exporting country controls the producer's price. It is found that, in a Markov-perfect Nash equilibrium, as the asymmetry between the importing countries increases, the aggregate welfare of the importing countries tends to be higher than under global free trade. The intuition is as follows. With two equally large buyers, the rivalry between them dilutes their market power. In contrast, when one buyer is small and the other is large, the large buyer is practically a monopsonist and can improve its welfare substantially, which means the sum of the welfare levels of both buyers is also larger. Rubio (2011) examines Markov-perfect Nash equilibriums in a dynamic game between a resource-exporting country and n identical noncooperative importing countries that set tariff rates. Rubio (2011) compares the case where the exporting country sets price and the case where it sets quantity. Using a numerical example, he finds that consumers are better off when the seller sets quantity.

Fujiwara and Long (2011) propose a dynamic game model of bilateral monopoly in a resource market where one of the country acts as a global Markovian Stackelberg leader in the sense that the leader announces a stock-dependent (i.e., Markovian) decision rule at the outset of the game, and then the follower chooses its response, also in the form of a stock-dependent decision rule.[24]

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[24] For discussions of the concept of global feedback Stackelberg equilibrium, see Basar and Olsder (1982) and Long and Sorger (2010). An alternative notion is the stagewise Stackelberg leadership, which will be explained in more detail in Sect. 3.3 below.

The resource-exporting country posts a price using a Markovian decision rule, $p = p(S)$, where S is the current level of the resource stock. The importing country sets a per-unit tariff rate τ which comes from a decision rule $\tau(S)$. The authors impose a time-consistency requirement which effectively restricts the set of strategies the leader can choose from. They show that the presence of a global Stackelberg leader leaves the follower worse off compared with its payoff in a Markov-perfect Nash equilibrium. Moreover, world welfare is highest in the Markov-perfect Nash equilibrium. These results are in sharp contrast with the results of Tahvonen (1996) and Rubio and Estriche (2001) who, using the concept of stagewise Stackelberg equilibrium, find that when the resource-exporting country is the leader, the stagewise Stackelberg equilibrium coincides with the Markov-perfect Nash equilibrium.[25]

In a companion paper, Fujiwara and Long (2012) consider the case where the resource-exporting country (called Foreign) determines the quantity to sell in each period. There are two resource-importing countries: a strategic, active country, called Home, and a passive country, called ROW (i.e., the rest of the world). The market for the extracted resource is integrated. Therefore Foreign's resource owners receive the same world price whether they export to Home or to ROW. Moreover, Home's consumers must pay a tax τ on top of the world price, while consumers in ROW only pay the world price. Home chooses τ to maximize Home's welfare. Fujiwara and Long (2012) show that, compared with the Markov-perfect Nash equilibrium, both countries are better off if Home is the global Markovian Stackelberg leader. However, if the resource-exporting country is the global Markovian Stackelberg leader, Home is worse off compared to its Markov-perfect Nash equilibrium welfare.

Finally, in managing international trade in fossil fuels, resource-exporting countries should take into account the fact that importing countries cannot be forced to pay a higher price than the cost of alternative energy sources that a backstop technology can provide. Hoel (1978) shows how a fossil-fuel monopolist's market power is constrained by the existence of a backstop technology that competitive firms can use to produce a substitute for the fossil fuels. This result has been generalized to the case with two markets (van der Meijden 2016). Hoel (2011) demonstrates that when different countries have different costs of using a backstop technology, the imposition of a carbon tax by one country may result in a "Green Paradox," i.e., in response to the carbon tax, the near-future extraction of fossil fuels may increase, bringing climate change damages closer to the present. Long and Staehler (2014) find that a technological advance in the backstop technology may result in a similar Green Paradox outcome. For a survey of the literature on the Green Paradox in open economies, see Long (2015b).

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[25] In a stagewise Stackelberg equilibrium, no commitment of any significant length is possible. The leader can only commit to the current period decision.

3.3 Fossil Resources and Pollution

Among the most important economic issues of the twenty-first century is the impending risk of substantial damages caused by climate change, which is inherently linked to an important class of exhaustible resources: fossil fuels, such as oil, natural gas, and coal. The publication of the Stern Review (2006) has provided impetus to economic analysis of climate change and policies toward fossil fuels. For a small sample of this large literature, see Heal (2009) and Haurie et al. (2011).

Wirl (1994) considers a dynamic game between a resource-exporting country and an importing country that suffers from the accumulated pollution which arises from the consumption of the resource, $y(t)$. Let $Z(t)$ denote the stock of pollution and $S(t)$ denote the stock of the exhaustible resource. Assume for simplicity that the natural rate of pollution decay is zero. Then $\dot{Z}(t) = y(t) = -\dot{S}(t)$, and hence $S(0) - S(t) = Z(t) - Z(0)$. The stock of pollution gives rise to the damage cost $DZ(t)^2$. The importing country imposes a carbon tax rate τ according to some Markovian rule $\tau(t) = g(Z(t))$. The exporting country follows a pricing rule $p(t) = \phi(S(t)) = \phi(Z(0) - Z(t) + S(0))$. Along the Markov-perfect Nash equilibrium, where $g(.)$ and $\phi(.)$ are noncooperative chosen by the importing country and the exporting country, it is found that the carbon tax rate will rise, and if $S(0)$ is sufficiently large, eventually the consumption of the exhaustible resource tends to zero while the remaining resource stock tends to some positive level $S_L > 0$. This is the case of economic exhaustion, because the equilibrium producer price falls to zero due to rising carbon taxation.

Tahvonen (1996) modifies the model of Wirl (1994) by allowing the exporting country to be a stagewise Stackelberg leader. As explained in Long (2011), if the time horizon is finite and time is discrete, stagewise leadership by the exporter means that in each period, the resource-exporting country moves first by announcing the well-head price p_t for that period. The government of the importing country (the stagewise follower) reacts to that price by imposing a carbon tax τ_t for that period. Working backward, each party's payoff for period $T-1$ can then be expressed as a function of the opening pollution stock, Z_{T-1}. Then, in period $T-2$, the price p_{T-2} is chosen and so on. For tractability, Tahvonen (1996) works with a model involving continuous time and an infinite horizon, which derives its justification by shrinking the length of each period and taking the limit as the time horizon becomes arbitrarily large. He finds that the stagewise Stackelberg equilibrium of this model coincides with the Markov-perfect Nash equilibrium.[26] Liski and Tahvonen (2004) decompose the carbon tax into a Pigouvian component and an optimal tariff component.

Different from the stagewise Stackelberg approach of Tahvonen (1996), Katayama et al. (2014) consider the implication of global Markovian Stackelberg leadership in a model a dynamic game involving a fossil-fuel-exporting cartel and

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[26] This result is confirmed by Rubio and Estriche (2001) who modify the model of Tahvonen (1996) by assuming that the per-unit extraction cost in period t is $c \times (S(0) - S(t))$, where c is a positive parameter.

a coalition of importing countries that suffer from accumulated emissions and impose a carbon tax on the fossil fuel. Referring to Fujiwara and Long (2011), who do not consider pollution, Katayama et al. (2014) impose a time-consistency requirement on the Markovian strategy of the global Stackelberg leader. They find that world welfare under the social planner is strictly greater than world welfare under the Markov-perfect Nash equilibrium, which in turn dominates world welfare when the exporting country is the global Stackelberg leader. When the coalition of the importing countries is the global Stackelberg leader, world welfare is lowest compared to the other scenarios. Finally, while the linear-quadratic structure is conducive to analytical solution, there is a need to go beyond that structure. Bearing this in mind, Kagan et al. (2015) take a big step forward in the analysis of resource depletion and climate change, with the help of advanced numerical techniques.

3.4 Extraction of Exhaustible Resources Under Common Access

In the preceding subsections, we have assumed that the property rights of the exhaustible resource stocks are well defined and well enforced. However, there are instances where some exhaustible resources are under common access. For examples, many oil fields are interconnected. Because of seepage, the owner of each oil field in fact can "steal" the oil of his neighbors. Under these conditions, the incentive for each owner to conserve his resource is not strong enough to ensure an efficient outcome. The belief that common access resources are extracted too fast has resulted in various regulations on extraction (McDonald 1971; Watkins 1977).

Khalatbary (1977) presents a model of m oligopolistic firms extracting from m interconnected oil fields. It is assumed that there is an exogenous seepage parameter $\beta > 0$ such that, if $E_i(t)$ denotes extraction from stock $S_i(t)$, the rate of change in $S_i(t)$ is

$$\dot{S}_i(t) = -E_i(t) - \beta S_i(t) + \frac{\beta}{m-1}\sum_{j \neq i} S_j(t)$$

The price of the extracted resource is $P = P\left(\sum E_j\right)$. Khalatbary (1977) assumes that firm i maximizes its integral of the flow of discounted profits, subject to a single transition equation, while taking the time paths of *both* $E_j(t)$ *and* $S_j(t)$ and as given, for all $j \neq i$. He shows that at the open-loop Nash equilibrium, the firms extract at a faster rate than they would if there were no seepage.[27] Kemp and Long (1980, p. 132) point out that firm i should realize that $S_j(t)$ is indirectly dependent on the time path of firm i's extraction, because $\dot{S}_j(t)$ depends on $S_i(t)$ which in turn is affected by firm i's path of extraction from time 0 up to time t. Thus, firm i's

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[27] Dasgupta and Heal (1979, Ch. 12) consider the open-loop Nash equilibrium of a similar seepage problem, with just two firms, and reach similar results.

dynamic optimization problem should include m transition equations, not just one, and thus, firm i can influence $S_j(t)$ indirectly.[28] Under this formulation, Kemp and Long (1980) find that the open-loop Nash equilibrium can be efficient.[29]

McMillan and Sinn (1984) propose that each firm conjectures that the extraction of other firms obeys a Markovian rule of the form $\alpha(t) + \gamma S(t)$ where $S(t)$ is the aggregate stock. Their objective is to determine $\alpha(t)$ and γ such that the expectations are fulfilled. They find that there are many equilibria. They obtain the open-loop results of Khalatbary (1977), Dasgupta and Heal (1979), Kemp and Long (1980), Bolle (1980), and Sinn (1984) as special cases: if $\gamma = 0$ and $\alpha(t)$ is the extraction path, one obtains an open-loop Nash equilibrium.

Laurent-Lucchetti and Santugini (2012) combine common property exhaustible resources with uncertainty about expropriation, as in Long (1975). Consider a host country that allows two firms to exploit a common resource stock under a contract that requires each firm to pay the host country a fraction τ of its profit. Under the initial agreement, $\tau = \tau_L$. However, there is uncertainty about how long the agreement will last. The host country can legislate a change in τ to a higher value, τ_H. It can also evict one of the firms. The probability that these changes occur is exogenous. Formulating the problem as a dynamic game between the two firms, in which the risk of expropriation is exogenous and the identity of the firm to be expropriated is unknown ex ante, the authors find that weak property rights have an ambiguous effect on present extraction. Their theoretical finding is consistent with the empirical evidence provided by in Deacon and Bohn (2000).

3.5 Effectiveness of Antibiotics as an Exhaustible Resource

The exhaustible resource model can be modified to study the Markov-perfect equilibrium rate of decrease in the effectiveness of drugs such as antibiotics, when users fail to take into account the externalities of their actions on the payoff of other users. In an editorial on 21 December 2013, titled “The Perils of Antibiotic Use on Farms,” the New York Times reported that:

> The rampant use of antibiotics in agriculture has been alarming. The drugs are given not just to treat sick animals, but added in low doses to animal feed or water to speed the growth of cattle, pigs and chickens, thus reducing costs for the producers. Such widespread use of antibiotics in healthy animals has stimulated the emergence of bacterial strains that are resistant to antibiotics and capable of passing their resistance to human pathogens, many of which can no longer be treated by drugs that were once effective against them.
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> Each year, at least two million Americans fall ill — and 23,000 die — from antibiotic-resistant infections. Doctors are partly to blame because many prescribe antibiotics for conditions like colds that can’t be cured with such drugs. The Centers for Disease Control

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[28] Sinn (1984) considers a different concept of equilibrium in the seepage model: each firm is committed to achieve a given time path of its stock.

[29] Bolle (1980) obtains a similar result, assuming that there is only one common stock that all m firms have equal access.

> and Prevention estimated in September that up to half of the antibiotics prescribed for humans are not needed or are used inappropriately. It added, however, that overuse of antibiotics on farms contributed to the problem.

This raises the question of how to regulate the use of antibiotics in an economy, given that other economies may have weaker regulations which help their farmers realize more profits in the short run, as compared with the profits in economies with stronger regulations. Cornes et al. (2001) consider two models of dynamic game on the use of antibiotics: a discrete-time model and a continuous-time model. Assume n players share a common pool, namely, the effectiveness of an antibiotic. Their accumulated use of the antibiotic decreases its effectiveness: the more they use the drug, the quicker the bacteria develop their resistance. The discrete-time model yields the result that there are several Markov-perfect Nash equilibria, with different time path of effectiveness. For the continuous-time model, there is a continuum of Markov-perfect Nash equilibria.

There are $n \geq 2$ countries. Let $S(t)$ denote the effectiveness of the antibiotic and $E_i(t)$ denote its rate of use in country i. The rate of decline of effectiveness is described in the following equation:

$$\dot{S}(t) = -\beta \sum\nolimits_{i=1}^{n} E_i(t), \beta > 0, \qquad S(0) = S_0 > 0.$$

Assume that the benefit to country i of using $E_i(t)$ is $B_i(t) = (S(t)E_i(t))^{\alpha}$, where $0 < \alpha < 1$. Call $E_i(t)$ the nominal dose and $S(t)E_i(t)$ the effective dose. If the countries coordinate their policies, the cooperative problem is to maximize the integral of discounted benefits, where $r > 0$ is the discount rate. The optimal cooperative policy rule is linear: $E_i(t) = rS(t)/2\beta n(1-\alpha)$. In the noncooperative scenario, each country uses a feedback strategy $E_i = \phi_i(S)$. Assuming that $\alpha < 1/n$, Cornes et al. (2001) find that there is a Markov-perfect Nash equilibrium where all countries use the linear strategy $E_i(t) = rS(t)/2\beta n(n^{-1} - \alpha)$. Thus, the effectiveness of the antibiotic declines at a faster rate than is socially optimal. Interestingly, in addition to the above linear strategy equilibrium, Cornes et al. (2001) show that there is a continuum of Markov-perfect Nash equilibria where all countries use nonlinear strategies, and S becomes zero at some finite time. Nonuniqueness has also been reported in Clemhout and Wan (1995).

Thus, when countries do not coordinate their policies on the use of biological assets, the result is overexploitation. Another problem of rivalry in a broader biological context is the biological arms race between species, as discussed in Dawkins and Krebs (1979). The lesson is that whatever biological techniques humans may devise in their efforts to exploit and utilize the resources that nature has to offer, we are likely to find ourselves in an arena in which our competitors will fight back. The continuing struggle is as old as life itself and indeed inseparable from it.

Herrmann and Gaudet (2009) also analyze the exploitation of antibiotic effectiveness in terms of a common pool problem. They think of a generic product which takes over once a patent has expired. The authors take into account the interaction between the level of efficacy of the drug and the level of infection in the population. The model is based on an epidemiological model from the biology literature. Unlike Cornes et al. (2001) and Herrmann and Gaudet (2009) do not formulate a differential game model, because they assume that no economic agent takes into account the dynamic effects of their decision.

4 Directions for Future Research

There are a number of issues in resource economics that remain under-explored. The first issue is the spatial dimension. Exhaustible resource stocks are unevenly distributed around the globe, and this fact necessitates the transportation of the extracted resources to consumers. How do resource-exporting firms located at different places compete with each other for customers over time and space? What would be the properties of Markov-perfect equilibrium involving spatially separated resource-extracting oligopolists?[30]

Similarly, renewable resources, such as fish stocks, are also dispersed in space. Harvesting fleets are not stationary: they typically have to travel and fish at many locations. Behringer and Upman (2014) model a fleet that moves along a circle to catch fishes. Their model involves both space and time. However, they do not address the issue of dynamic games (across space and time) among different fleets, and they assume that fish do not move from one pool to another. Modeling dynamic fishing strategies when fish move from one place to another is surely a challenging research topic.[31]

The second topic that deserves exploring is learning about the properties of resources that one exploit, for example, discovering more precise information about the growth function of a resource stock. Mirman and Santugini (2014) have made a useful step in this direction. A third topic is how to provide incentives for cooperation. In this context, we note that de Frutos and Martín-Herrán (2015) provide useful analysis of a generalized concept of incentive equilibrium such that players' behavior (including a Markovian type of punishment) ensures that the system is sufficiently close to the fully cooperative equilibrium outcome. They also give a very clear definition of the concept of incentive equilibrium, an informative historical account of the development and application of this concept, and show how to compute such equilibria numerically. However, since in their example, de Frutos and Martín-Herrán (2015) restrict attention to the linear-quadratic case, much work remains to be done for a general treatment.

The fourth issue is the political economy of resource conservation. The majority of the current electorate may have very little interest in conserving natural resources. Governments may have to balance the need of future generations with the

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[30] The case of open-loop Nash equilibrium was addressed by Kolstad (1994) and Keutiben (2014).

[31] This is related to the so-called SLOSS debate in ecology, in which authors disagree as to whether a single large or several small (SLOSS) reserves would be better for conservation.

impatience of the current voters. What would be an appropriate formulation of the dynamic games among generations? One possible way of addressing this problem is to think of the political process as the dual-self problem, as in Fudenberg and Levine (2002, 2012).

Finally, it is high time to depart from the assumption that all players are selfish. Dynamic game models of natural resource exploitation typically rely on that assumption, which clearly leads to the prediction of overexploitation of many resource stocks. However, as Ostrom (1990) points out, in some societies, good social norms are sufficiently developed to avoid the tragedy of the commons. What would be the dynamic evolution of resource stocks if some kinds of social norms are developed to guide the behavior of economic agents?[32] The importance of social norms was recognized by classical economists. Adam Smith (1790) finds that cooperation and mutual help are incorporated in established norms of behavior and that

> upon the tolerable observance of these duties, depend the very existence of human society, which would **crumble into nothing** if mankind were not generally impressed with a reverence for those important rules of conduct. (Smith 1790, Part III, Chap. V, p. 190)

Clearly, Smith's view is that for societies to prosper, there is a need for two invisible hands, not just one. First is the moral invisible hand that encourages the observance of duties; second is the invisible hand of the price system, which guides the allocation of resources. Along the same lines, Roemer (2010, 2015) formulates the concept of Kantian equilibrium, for games in which players are imbued with Kantian ethics (Russell 1945). By definition, this equilibrium is a state of affairs in which players of a common property resource game would not deviate when each finds that if she was to deviate and everyone else would do likewise, she would be worse off. However, Roemer (2010, 2015) restricts attention to static games, as does Long (2016a,b) for the case of mixed strategy Kantian equilibria. Dynamic extension of the concept of Kantian equilibrium has been explored by Long (2015a) and Grafton et al. (2016), who also defined the concept of dynamic Kant-Nash equilibrium to account for the coexistence of Kantian agents and Nashian agents. However, Long (2015a) and Grafton et al. (2016) did not deal with the issue of how the proportion of Kantian agents may change over time, due to learning or social influence. Introducing evolutionary elements into this type of model remains a challenge.[33]

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[32] Myerson and Weibull (2015) formalize the idea that "social conventions usually develop so that people tend to disregard alternatives outside the convention."

[33] For a sample of papers that deal with evolutionary dynamics, see Bala and Long (2005), Breton et al. (2010), and Sethi and Somanathan (1996).

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