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Ownership Risk and the Use of Common-Pool Natural Resources*

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Abstract

It has long been recognized that the quality of property rights greatly impacts the economic development of a country and the use of its natural resources. Since Long (1975), the conventional wisdom has been that ownership risk induces a firm to overuse the stock of a resource. However, the empirical evidence is mixed. In particular, Bohn and Deacon (2000) finds that weak property rights have an ambiguous effect on present extraction. We provide a theoretical model supporting these mixed observations in a common-pool resource environment. We show that if ownership risk includes a risk of expropriation in which the identities of the excluded firms are unknown *ex ante*, then the present extraction of all firms may decrease along with a higher risk of expropriation. The elasticity of demand for the resource is key in explaining the effect of ownership risk on present extraction.

Keywords: Common-pool resource, Expropriation, Extraction behavior, Ownership risk, Property rights, Tragedy of the commons.
JEL Classifications: D21, D23, D92, Q30.

1 Introduction

It has long been recognized that the quality of property rights greatly impacts the economic development of a country and the use of its natural resources. The issue of property rights is particularly relevant in the resource sector because numerous resource-rich countries have weak property rights due to unreliable judicial systems and/or unstable political environment. Since Long (1975), the conventional wisdom has been that ownership risk induces a firm to overuse the stock of a resource.[1] Specifically, a higher risk of expropriation decreases the marginal return of exploiting the stock in the future, which raises present extraction.[2] In other words, increasing the risk of expropriation causes the future return from maintaining the stock to be discounted more heavily, which leads to disinvestment. This explanation has been supported by empirical evidence, notably Jacoby et al. (2002).[3]

An empirical study by Bohn and Deacon (2000) challenges this vision. Using cross-country data compiled from various sources, weaker property rights are shown to have an ambiguous effect on the use of natural resources. In particular, weaker property rights reduces the current extraction for resources such as petroleum and mining that need large up-front expenditure in capital goods. This is because higher ownership risk deters the large up-front expenditures necessary to exploit the resource, which, in turn, reduces present extraction.[4] However, one can wonder why countries such as Bolivia, Venezuela, or Russia have managed to attract large amounts of foreign-direct investment (FDI) in petroleum and mining despite a history of nationalization and expropriation of foreign interests in these sectors (Kobrin, 1984;

[1] *Weak property rights* and *ownership risk* are used interchangeably in the text. Both terms refer to the uncertainty about the agreements between a country and the firms regarding the exploitation of a natural resource.

[2] Expropriation may refer not only to the physical exclusion of the firm, but also to the appropriation of some of the profits generated from the exploitation of the resource.

[3] Using household data from northeast China, Jacoby et al. (2002) study the link between investment in fertilizer use and land tenure insecurity induced by China's system of village-level land reallocation. They show that a higher risk of expropriation significantly reduces private long run investments.

[4] Note that the explanation put forth by Bohn and Deacon (2000) is related to Farzin (1984) and Lasserre (1985) which show that a higher discount rate leads to lower current extraction if the extraction process is sufficiently capital-intensive.

Kennedy, 1993). More generally, using a panel data of 42 developing countries for the 1993-2006 period, Hajzler (2008) shows that countries viewed as more likely to expropriate (having expropriated in the recent past) also have a disproportionate share of FDI in the resource sector, even for the resources asking for large up-front expenditures. In other words, investment in countries with a high risk of expropriation is not only *large*, but it is also *larger* than in countries with a low risk of expropriation. Specifically, the average share of resources in total FDI is higher among recently expropriating countries in comparison to non-expropriating countries, even if expropriating countries are not especially resource-dependent (Hajzler, 2008).[5]

We provide a theoretical model supporting these mixed observations in a traditional common-pool resource environment. We show that if ownership risk includes a risk of expropriation in which the identities of the excluded firms are unknown *ex ante*, then present extraction may decrease along with a higher risk of expropriation. To see why, consider a small group of firms that are presently exploiting a resource in a politically unstable country. The anticipation of a sudden change in the agreement with the expropriation of some of the firms has an ambiguous effect on future profits. While the exclusion of a firm reduces its own future profits to zero, the exclusion of some of the other firms increases future profits due to less competition in extracting the resource. Hence, a higher risk of expropriation has two effects on the behavior of a firm through its anticipated payoffs. On the one hand, a firm has a higher incentive to extract the resource now due to a lower chance of reaping the future reward if affected by expropriation. On the other hand, a firm has a higher incentive to manage the resource in the long run due to a chance of facing less competition if it happens that the other firms are expropriated. These two incentives work in opposite direction, and, thus, the overall effect of weaker property rights on behavior depends on their respective strength: if the expected gain from less competition outweighs the

[5] Note that, due to the unobservability of other terms of the agreements that could have offset expropriation risks, we cannot unambiguously state exactly how larger FDI would have been in each country with a lower expropriation risk. However, these examples and results provide a motivation to offer an alternative explanation that does not rely on the capital intensity of extraction resource.

expected loss from being expropriated, then present extraction decreases in response to weaker property rights. Two stylized facts support our explanation. First, the resource extraction sector is mainly a sector with a few extracting firms (Salant, 1976; Dasgupta and Stiglitz, 1981; Hartwick and Sadorsky, 1990), which is prone to the tragedy of the common (Tornell and Velasco, 1992; Tornell and Lane, 1999; Van der Ploeg, 2010). Second, there are very few massive expropriations in which all the firms extracting a common resource are expropriated at the same time. In 42 developing countries, from 1989 to 2006, 77% of episodes of expropriations affected only one firm. Data from Hajzler (2008).

In order to embed formally the uncertainty in the number of firms exploiting a common resource, it is necessary to depart from the traditional single-firm framework used in the literature (Long, 1975; Bohn and Deacon, 2000). Therefore, we study the question of ownership risk in an infinite-horizon dynamic game with two firms earning a profit from the exploitation of a common and nonrenewable resource.[6] Each firm is a monopolist in the sale of the resource, but competes with one another in the exploitation of the resource. Hence, the effect of a firm on the other firm's payoffs is realized through the evolution of the stock. In other words, there is a dynamic externality leading to the tragedy of the commons.[7]

The exploitation of the resource is governed by an agreement between a country and the two firms. The agreement defines the identities of the active firms allowed to exploit the resource, as well as the cost of extraction

[6]Absent expropriation, extraction activities are usually long-term projects. The game can be solved recursively for large finite horizons as well. The limit of the solution for the t-period game as t goes to infinity is the solution to the infinite-horizon game that we consider. See Levhari and Mirman (1980) for a canonical example. The important point is that our explanation (i.e., if ownership risk includes a risk of expropriation in which the identities of the excluded firms are unknown *ex ante*, then present extraction may decrease along with a higher risk of expropriation) is robust to the horizon of the game. However, given the specification of the game, shorter horizons reinforce the negative effect of ownership risk on present extraction. Hence, the infinite horizon provides the weakest conditions for which a higher risk of ownership leads to a lower present extraction.

[7]In order to obtain a clear exposition of the mechanism at work, we abstract from the interaction of the two firms in the resale market. We later show in Section 4 and Appendix C that our results are robust to a model in which firms also interact in the resale market.

rights for each active firm. The country has weak property rights because the agreement is subject to a one-time change. The probability of a change in the agreement is exogenous and known to all firms. The sudden change in the agreement can lead to the expropriation of one of the firms (so that the remaining firm no longer faces a dynamic externality) or the unilateral increase in the cost of extraction rights or both.[8] While ownership risk has two components, the change in the cost of extraction rights applies to both firms, while the exclusion affects at most one firm. Specifically, a higher risk of exclusion means that there is a higher probability that one of the two firms be excluded, although the identity of the excluded firm is unknown *ex ante*. Note that we do not look at appropriation games in which powerful groups can influence the fiscal process and redistribute the economy-wide capital stock among themselves (Tornell and Velasco, 1992; Tornell and Lane, 1999) or at contracting games between the firms and the government. As in Long (1975) and Bohn and Deacon (2000), our paper focuses on the effect of an exogenous ownership risk on behavior of firms. Considering an endogenous property right environment is outside of the scope of this paper. See Hotte et al. (2000) for a recent contribution on this topic.

After characterizing the behavior of the firms in the symmetric Markov-perfect equilibrium, we study the effect of ownership risk on the present exploitation of the resource. Our results can be summarized as follows. First, if there is no risk of expropriation, then a higher likelihood of a unilateral increase in the cost of extraction rights (in the form of a higher share of profit retained by the country) induces all the firms to extract more in the present. This result is a generalization to games of the risk of expropriation studied

[8]Considering both sources of ownership risk is relevant with regard to what happens in practice. For example, Venezuela used both during its history of nationalization. Over the years, there has been significant increases in the income tax rate applicable to the oil activity as well as the approval of additional surcharge taxes. These taxes increased from about 50% in the forties and fifties to a maximum of 94% in the seventies (Monaldi, 2008). During the privatization wave in the nineties, royalty rates had been reduced to a mere 1% of revenues for many foreign firms. In 2004, these royalties were increased to 16% of the benefits and in 2006 these royalties represented up to 50% of the benefits. Regarding the exclusion of firms, Exxon and several other foreign companies have recently had their assets seized by the Venezuelan state: at least $1.7 billion in mining and petroleum investments has been expropriated between 2001 and 2006.

in a single-firm framework by Long (1975) and Bohn and Deacon (2000).[9]

Second, the risk of expropriation yields an ambiguous effect on present extraction regardless of the presence of the risk of a higher cost of extraction rights. That is, a higher probability that one of the two firms be excluded in the future might decrease present extraction for both firms. The direction of this effect depends on the elasticity of demand. The key role of the elasticity of demand is related to the tragedy of the commons.[10] Specifically, a higher elasticity of demand exacerbates the tragedy of the commons, i.e., the negative impact of the dynamic externality on profits increases on the elasticity of demand. In other words, while an increase in demand elasticity increases extraction for both a single firm and a group of competing firms, the difference is increasing in the elasticity of demand. Therefore, in a situation of a *strong* tragedy of the commons (due to a high elasticity of demand), the expected gain from less competition outweighs the expected loss from being expropriated, which decreases present extraction when ownership risk increases.[11] However, for low values of the elasticity of demand yielding a *weak* tragedy of the commons, the marginal loss of being excluded is the strongest effect. Thus, both firms increase extraction as ownership risk increases.

The remainder of the paper proceeds as follows. In Section 2, we present the model and characterize the dynamic Cournot-Nash equilibrium. In Section 3, we study the effect of ownership risk on optimal behavior. Section 4 concludes.

[9] Our model encompasses the extreme case of a nationalization of the natural resource and a full expropriation of both firms when the cost of extraction rights after the sudden change in the agreement is such that the entire profits of the firms are retained by the country.

[10] See Koulovatianos and Mirman (2007) for the role of the elasticity of demand regarding the effect of externalities on the behavior of the firms.

[11] This is akin to an intertemporal third degree price discrimination in a monopolistic market. Indeed, as the price elasticity becomes larger in future, it is more profitable to extract less now and charge a higher price in order to shift more of the extraction to the future. We thank an anonymous referee for this point.

2 The Model

2.1 Preliminaries

Consider a country in which two firms earn a profit from the exploitation of a common and nonrenewable resource. The exploitation of the resource is governed by an agreement between a country and the two firms. The agreement defines the identities of the *active* firms allowed to exploit the resource, as well as the division of the profit between the country and each active firm. Let $\mathcal{F}_t$ be the set of active firms and $\tau_t \in [0,1]$ be the share of profit each active firm pays to the country at time t. Hence, τ_t is a tax and characterizes the cost of extraction rights.[12] Assumption 2.1 specifies the types of agreements the firms may face.

Assumption 2.1. $\mathcal{F}_t \in \{\{1,2\},\{1\},\{2\}\}$ *and* $\tau_t \in \{\underline{\tau},\overline{\tau}\}$, $\underline{\tau} < \overline{\tau}$.

At time t, $\mathcal{F}_t = \{1,2\}$ refers to an environment with a dynamic externality in which firms 1 and 2 exploit the resource, while $\mathcal{F}_t = \{j\}$ means that firm j is allowed to exploit the resource, while firm k is excluded, $k \neq j$. Under the initial agreement, both firms are active and retain a higher share of their profits, i.e., $\mathcal{F}_t = \{1,2\}$ and $\tau_t = \underline{\tau}$. Ownership risk is present because the initial agreement is uncertain and subject to changes in both the cost of extraction rights as well as the identities of the firms allowed to exploit the resource. Assumptions 2.2 and 2.3 specify the uncertainty in the agreement.[13] The event leading to a change in the initial agreement occurs only once with known and exogenous probability. The probability distribution of this event is discrete and time independent, i.e., it does not change with time until the eviction happens. Once the event occurs, uncertainty disappears for the remaining periods.[14] Moreover, under the new agreement, each firm has an equal probability to remain active.

[12]While the tax is imposed on the profit, it is possible to tax the quantity extracted as well.

[13]The tilde distinguishes a random variable from its realization.

[14]A different set up in which the eviction date is certain, but the identity of the excluded firm is a random exogenous event retains the same trade-off we have identified because each firm has the possibility to remain the sole firm after the eviction date. If the event happens very soon (or if the discounting is very low), then it is akin to have a high probability of

Assumption 2.2. *For* $j = 1, 2$ *and* $\rho \in [0, 1]$, $\Pr[\tilde{\mathcal{F}}_{t+1} = \{j\} | \mathcal{F}_t = \{1, 2\}, \tau_t = \underline{\tau}] = \rho/2$ *and* $\Pr[\tilde{\mathcal{F}}_{t+1} = \{j\} | \mathcal{F}_t = \{j\}] = \Pr[\tilde{\mathcal{F}}_{t+1} = \{1, 2\} | \mathcal{F}_t = \{1, 2\}, \tau_t = \overline{\tau}] = 1$.

Assumption 2.3. *For* $j = 1, 2$ *and* $\alpha \in [0, 1]$, $\Pr[\tilde{\tau}_{t+1} = \overline{\tau} | \tau_t = \underline{\tau}, \mathcal{F}_t = \{1, 2\}] = \alpha$ *and* $\Pr[\tilde{\tau}_{t+1} = \overline{\tau} | \tau_t = \overline{\tau}] = \Pr[\tilde{\tau}_{t+1} = \overline{\tau} | \tau_t = \underline{\tau}, \mathcal{F}_t = \{j\}] = 1$.

A few comments about Assumptions 2.2 and 2.3 are warranted. First, the assumed probability distributions allow us to study several cases of uncertainty in property rights. If $\rho > 0$ and $\alpha = 0$, then the uncertainty emanates only from the number of active firms. If $\rho = 0$ and $\alpha > 0$, then the firms expect a possible alteration only in the tax levied by the country. Finally, the case of $\rho > 0$ and $\alpha > 0$ combines both sources of uncertainty in property rights. All these cases can then be compared to the benchmark case of no uncertainty with $\rho = \alpha = 0$.

Second, our specification embeds the case of full expropriation as studied in the single-firm framework by Long (1975) and Bohn and Deacon (2000).[15] Indeed, $\rho = 0$ and $\overline{\tau} = 1$ refers to the situation in which the government capture all profits, which amounts to an expropriation of *all* firms and a nationalization of the natural resource industry. Here, $\rho > 0$ refers to a partial expropriation with one firm excluded and one firm remaining active in the industry. As ρ increases, both firms face a equally higher probability to be excluded.

Last, the presence of several sources of risk in the agreement has an ambiguous effect on a firm's welfare. For instance, suppose that a political coup leads to the exclusion of firm k, while levying a higher tax on the remaining firm j, $j \neq k$. While firm j no longer faces competition in the exploitation of the resource, it retains less of its profit.

eviction on our model, and if the event happens far in the future (or if the discounting is very high), then it corresponds to a low probability of exclusion in our set up.

[15] Note that we ignore the distinction between full expropriation in the sense of taxing all profits and that of confiscating a firm's invested capital. The difference might be reflected in the outside option which we have normalized to zero. Indeed, if all profits are taxed, then the firm retains its capital, which translates into a higher value of the outside option. If invested capital is confiscated, then the value of the outside option of the firm is reduced.

Having discussed all aspects of the agreement, we now describe the evolution of the stock and the objective function of the firm.[16] The stock of the resource available to the active firms at time t is y_t. Each period, firm $j \in \mathcal{F}_t$ extracts a quantity $q_{j,t}$, which yields a profit $\pi(q_{j,t}) = P_{j,t}q_{j,t}$. The cost is normalized to zero for simplicity. Here, each firm is always monopolistic in the market, i.e., $P_{j,t} = q_{j,t}^{-\frac{1}{\eta}}$ where $\eta > 1$ is the elasticity of demand.[17] Under any agreement, $(1 - \tau_t)\pi(q_{j,t})$ is retained by the firm and $\tau_t\pi(q_{j,t})$ is paid to the country.

The present overall exploitation by the active firms has an effect on the future stock of the common resource. At time t, a total quantity $\sum_{j\in\mathcal{F}_t} q_{j,t}$ of the resource is extracted and the remaining $y_t - \sum_{j\in\mathcal{F}_t} q_{j,t}$ is left for future exploitation, so that the evolution of the exploited resource follows the rule

$$y_{t+1} = y_t - \sum_{j\in\mathcal{F}_t} q_{j,t}. \tag{1}$$

2.2 Maximization Problem

We consider the maximization problem of an active firm in a dynamic infinite-horizon Cournot-Nash game. Since we restrict attention to stationary Markovian strategies, the problem at hand is time-independent and the subscript t is dropped hereafter. To distinguish between present and future values, the prime sign is used. For instance, y and y' are the stock of the resource today and tomorrow, respectively, while $\tilde{\mathcal{F}}'$ is the random set of active firms tomorrow.

Given the stock y, the set of active firms $\mathcal{F}$, and the cost of extraction rights, τ, each firm maximizes the expected sum of discounted profits over quantities. To that end, each firm anticipates the effect of his present exploitation as well as the effect of the other firm's output decision on the future stock of the resource. Moreover, each firm anticipates the possibility of an irreversible change in the agreement. Therefore, the value function of

[16] Koulovatianos and Mirman (2007) use a similar (more general) dynamic framework to study the effect of market and dynamic externalities on strategies and industry growth.

[17] Introducing a duopolistic market has no substantial effect on our results. See Section 4 for a discussion.

firm $j \in \mathcal{F}$ is

$$V_j(y, \mathcal{F}, \tau) = \max_{q_j} \; (1-\tau) q_j^{1-\frac{1}{\eta}} + \delta E V_j(y', \tilde{\mathcal{F}}', \tilde{\tau}'), \tag{2}$$

for $0 \leq q_j \leq y - q_k 1_{[k \in \mathcal{F}]}$, $k \neq j$.[18] Here, from (1), $y' = y - q_j - q_k 1_{[k \in \mathcal{F}]}$ is the stock of the resource available tomorrow, and the expectation operator E over the random variables $\tilde{\mathcal{F}}'$ and $\tilde{\tau}'$ conditional on $\mathcal{F}$ and τ characterizes the uncertainty about the agreement. From (2), firm j faces a dynamic externality through the evolution of the stock of the resource.

Using Assumptions 2.1, 2.2, and 2.3, we focus on the behavior of the firms under the initial agreement. Specifically, both firms are presently allowed to extract the resource and retain more of their profits, i.e., $\mathcal{F} = \{1, 2\}$ and $\tau = \underline{\tau}$. Under the initial agreement, (2) is rewritten as

$$\begin{aligned} V_j(y, \{1,2\}, \underline{\tau}) = &\max_{q_j} \; (1-\underline{\tau}) q_j^{1-\frac{1}{\eta}} + \delta(1-\rho)(1-\alpha) V_j(y - q_j - q_k, \{1,2\}, \underline{\tau}) \\ &+ \delta(1-\rho)\alpha V_j(y - q_j - q_k, \{1,2\}, \overline{\tau}) \\ &+ \delta\rho(1-\alpha) V_j(y - q_j - q_k, \{j\}, \underline{\tau})/2 \\ &+ \delta\rho\alpha V_j(y - q_j - q_k, \{j\}, \overline{\tau})/2. \end{aligned} \tag{3}$$

In (3), firm j anticipates a possible change in the agreement in the subsequent period. Specifically, with probability $(1-\rho)(1-\alpha)$, the agreement remains the same, i.e., both firms remain active for at least one more period and each firm continues to retain a fraction $1-\underline{\tau}$ of the profit. With probability $(1-\rho)\alpha$, both firms remain active, but each firm retains a lower fraction of the profit. With probability $\rho(1-\alpha)/2$, firm k is excluded, while leaving unchanged the tax levied on the remaining firm j. With probability $\rho\alpha/2$, the change in the agreement leads to the exclusion of firm k as well as reduces the share of profit retained by firm j. Finally, with probability $\rho/2$, it is firm j that is excluded from extracting the resource, i.e., $\mathcal{F} = \{k\}$, and the anticipated stream of profits from the alternative activity for firm j is exogenous and normalized to zero. Consistent with Assumptions 2.2 and 2.3, once the agreement is

[18] The indicator function $1_{[k \in \mathcal{F}]}$ is equal to one when $k \in \mathcal{F}$, and zero otherwise.

modified, there are no more anticipated changes in the agreement. In other words, for any level of the stock y and $\{\mathcal{F}, \tau\} \neq \{\{1,2\}, \underline{\tau}\}$,

$$V_j(y, \mathcal{F}, \tau) = \max_{q_j} \; 1_{[j \in \mathcal{F}]}(1-\tau) q_j^{1-\frac{1}{\eta}} + \delta V_j(y - q_j - q_k 1_{[k \in \mathcal{F}]}, \mathcal{F}, \tau), \tag{4}$$

where $\{\mathcal{F}', \tau'\} = \{\mathcal{F}, \tau\}$.

2.3 Dynamic Cournot-Nash Equilibrium

We can now characterize the symmetric dynamic Cournot-Nash equilibrium corresponding to (2) under our assumptions.[19] Let $g(y, \mathcal{F}, \tau)$ be a stationary Markovian strategy for the present exploitation of the resource. The strategy profile $\{g(y, \mathcal{F}, \tau)\}_{j \in \mathcal{F}}$ is a symmetric Markov-perfect Nash equilibrium if the maximization problem (2) subject to $q_k = g(y, \mathcal{F}, \tau)$ yields the optimal solution $q_j = g(y, \mathcal{F}, \tau)$.

In view of (3) and (4), there are four different value functions. Proposition 2.4 provides the four value functions and their corresponding maximizers.[20] In Proposition 2.4, the terms $\varphi_{\mathcal{F},\tau} > 0$ and $\omega_{\mathcal{F},\tau} \in [0, 1/|\mathcal{F}|]$ depend only on the states $\mathcal{F}$ and τ, but not on y. These terms also depend on the exogenous parameters ρ, α, and η.

Proposition 2.4. *From* (2),

$$V(y, \mathcal{F}, \tau) = \varphi_{\mathcal{F},\tau} y^{1-\frac{1}{\eta}}, \tag{5}$$

and the optimal strategy is of the form

$$g(y, \mathcal{F}, \tau) = \omega_{\mathcal{F},\tau} y. \tag{6}$$

[19] Symmetry of the firms regarding the cost of extraction rights. Adding more heterogeneity in the cost of extraction rights and the probability of being excluded from the new agreement does not alter the results of the paper. It is in fact through heterogeneity that the ambiguity of the effect of ownership risk on behavior can be explained.

[20] The game can be solved recursively for finite horizons as well. The limit of the solution for the t-period game as t goes to infinity is the solution to the infinite-horizon game that we consider. See Levhari and Mirman (1980) for a canonical example.

The proof is relegated to Appendix A. Here, the cases with one firm have closed-form solutions, i.e., for $\tau \in \{\underline{\tau}, \overline{\tau}\}$,

$$V_j(y, \{j\}, \tau) = (1-\tau)(1-\delta^\eta)^{-\frac{1}{\eta}} y^{1-\frac{1}{\eta}}, \tag{7}$$

and $g(y, \{j\}, \tau) = (1-\delta^\eta)y$. The cases with two active firms do not have closed-form solutions. The value function with two firms and under a new agreement with a higher tax is

$$V(y, \{1,2\}, \overline{\tau}) = \frac{(1-\overline{\tau})\omega_{\{1,2\},\overline{\tau}}^{1-\frac{1}{\eta}}}{1-\delta(1-2\omega_{\{1,2\},\overline{\tau}})^{1-\frac{1}{\eta}}} y^{1-\frac{1}{\eta}} \tag{8}$$

and $g(y, \{1,2\}, \overline{\tau}) = \omega_{\{1,2\},\overline{\tau}} y$, where $\omega_{\{1,2\},\overline{\tau}} \in (0, 1/2)$ is implicitly defined by $\delta(1-\omega_{\{1,2\},\tau}) = (1-2\omega_{\{1,2\},\overline{\tau}})^{\frac{1}{\eta}}$. The case of the value function under the initial agreement defined by (3) is more elaborate because it combines the four value functions. The details can be found in Appendix A.

3 The Effect of Ownership Risk

Having characterized the equilibrium, we now study the effect of ownership risk on the present exploitation of the resource. To that end, we perform a numerical analysis using the symmetric optimal extraction under the initial agreement. From Proposition 2.4, the symmetric optimal extraction is defined by the first-order condition corresponding to (3),

$$\begin{aligned}(1-\underline{\tau})q^{-\frac{1}{\eta}} = {}& \delta(1-\rho)(1-\alpha)\varphi_{\{1,2\},\underline{\tau}}(y-2q)^{-\frac{1}{\eta}} + \delta(1-\rho)\alpha\varphi_{\{1,2\},\overline{\tau}}(y-2q)^{-\frac{1}{\eta}} \\ & + \delta\rho(1-\alpha)\varphi_{\{j\},\underline{\tau}}(y-2q)^{-\frac{1}{\eta}}/2 + \delta\rho\alpha\varphi_{\{j\},\overline{\tau}}(y-2q)^{-\frac{1}{\eta}}/2,\end{aligned} \tag{9}$$

evaluated at $q = g(y, \{1,2\}, \underline{\tau})$. Each firm's optimal extraction equates the marginal present profit of output with the discounted expected marginal profit of investment. The right-hand side of (9) has four components corresponding to the four possible scenarios in the future. The first term represents the marginal profit of investment conditional on remaining under the same agreement for at least one period, taking account of a possible alteration in the agreement later on. The last three terms represent the marginal profit of investment on experiencing an alteration in the agreement regarding either the number of active firms, or the cost of extraction rights, or both. The four terms are discounted by δ and weighed appropriately by the probability of a change in the agreement.

Our results can be summarized as follows. First, if ownership risk affects more than one aspect of the agreement, i.e., $\rho, \alpha > 0$, then the conventional wisdom does not hold. Specifically, if the likelihood of any type of ownership risk increases, then present extraction might decrease. We then separately study each type of ownership risk. We first discuss the effect of uncertainty in the cost of extraction rights when firms are certain to remain active. If changes in the cost of extraction rights are unilateral and apply identically to both firms, then the uncertainty in the cost of extraction rights yields the usual effect. That is, the conventional wisdom is extended to games if the only source of risk is the cost of extraction and changes are unilateral. We then study the effect of uncertainty in the number of firms allowed to exploit the resource when the cost of extraction rights cannot change. The uncertainty in the number of firms alone does yield an ambiguous effect.

Since, from Proposition 2.4, $g(y, \{1,2\}, \underline{\tau}) = \omega_{\{1,2\},\underline{\tau}} y$ is linear in y, we focus on the extraction rate $\omega_{\{1,2\},\underline{\tau}}$. To generate the graphs, we set $\delta = 0.98$, and consider the cases of $\eta \in \{1.01, 1.5, 2, 2.5\}$ and $(1-\underline{\tau})/(1-\overline{\tau}) \in \{1.2, 1.5, 2, 3\}$.[21] Note that $g(y, \mathcal{F}, \tau)$ depends on the tax rates only through the ratio $(1-\underline{\tau})/(1-\overline{\tau})$.[22] Here, $(1-\underline{\tau})/(1-\overline{\tau}) = 2$ means that the active firms would lose half of their profits if the tax was changed under the new agreement.

Our first remark considers the full model in which both types of ownership risk are at work, i.e., $\rho, \alpha > 0$.

Remark 3.1. *If ownership risk affects more than one aspect of the agreement, i.e., $\rho, \alpha > 0$, then an increase in the likelihood of any types of risk*

[21] The matlab codes to solve for the equilibrium and generate the graphs are available upon request.

[22] See (23) and (29) in Appendix A.

may decrease present extraction.

Remark 3.1 is illustrated in Figures 5, 6, 7 and 8 in Appendix D. Consistent with Remark 3.1, the Figures demonstrate that ownership risk has in general ambiguous effects on the extraction rate. We now study the two sources of ownership risk separately.

3.1 Risk in the Cost of Extraction Rights

Having established that the presence of several sources of ownership risk renders the relation between ownership risk and extraction behavior ambiguous, we now focus on the case of risk in the cost of extraction rights alone, i.e., $\rho = 0$ and $\alpha \geq 0$. From Proposition 3.2, the present exploitation increases in the probability of a change in the division of the profit which is detrimental to the firm. The present exploitation increases in the tax levied after the change in the agreement. Finally, the present exploitation decreases in the present tax, i.e., the present tax is distortionary. The proof is relegated to Appendix A.

Proposition 3.2. *Suppose that* $\rho = 0$ *and* $\alpha \geq 0$*. From* (9)*,* $g(y, \{1, 2\}, \underline{\tau})$ *is increasing in* α *and* $\overline{\tau}$*, and decreasing in* $\underline{\tau}$*.*

These findings are consistent with the conventional wisdom: a higher probability of being highly taxed leads to a higher rate of extraction of the resource (due to a lower expected profit in the future). The unambiguity of the results follows from the fact that the marginal profit of investment is decreasing in α and $\overline{\tau}$, and increasing in $\underline{\tau}$. Note that the unambiguity does not remain if the risk of exclusion is added to the risk of a higher cost of extraction rights. In other words, if $\rho > 0$, $\partial\omega_{\{1,2\},\underline{\tau}}/\partial\alpha$ cannot be signed. As mentioned earlier, this is shown to be the case when the elasticity of demand is low. See Figure 5.

Uncertainty only in the cost of extraction rights is analogous to what was studied previously in the literature. The case of $\overline{\tau} = 1$ is in fact equivalent to a nationalization of the natural resource and a full expropriation of all firms, as in Long (1975) and Bohn and Deacon (2000). We extend the conventional wisdom in a game situation, i.e., a higher likelihood of a higher tax in the future induces the firms to extract more in the present.

Remark 3.3. *If changes in the cost of extraction rights are unilateral (i.e., apply identically to both firms), then the uncertainty in the cost of extraction rights yields the usual effect of increasing present extraction.*

Proposition 3.2 and Remark 3.3 are illustrated in Figures 9, 10, 11, and 12 in Appendix D. Indeed, an increase in the likelihood of a higher cost of extraction rights increases present extraction.

3.2 Uncertainty in the Number of Active Firms

We next consider the case of uncertainty in the number of active firms alone, i.e., $\rho \geq 0$ and $\alpha = 0$. Here, a higher probability of being excluded or remaining the only active firm in the future has an ambiguous effect on present extraction. Figure 1 illustrates the effect of uncertainty in the number of active firms on present extraction rate.

Proposition 3.4. *Suppose that $\rho \geq 0$ and $\alpha = 0$. From* (9)*, $\partial g(y, \{1, 2\}, \underline{\tau})/\partial \rho$ cannot be signed.*

The elasticity of demand is a key factor for explaining the behavior of firms in face of the risk of expropriation. This is seen in Figure 1 which relates the extraction rate under the initial agreement and the risk of exclusion. For high values of the elasticity of demand (i.e., $\eta = \{2, 2.5\}$), the marginal loss of being expropriated is smaller than the marginal gain of facing less competition, and, thus, more ownership risk leads to a decrease in present extraction. However, for low values of the elasticity of demand, the marginal gain of facing less competition is weakest, which induces firms to increase extraction as ownership risk increases.[23]

[23] Note that the size of the stock does not matter for the effects of ownership risk because strategies are linear in the stock, and, thus, extraction rates are independent of the stock. It is unclear whether the size of the stock would matter in a more general model with nonlinear strategies. Indeed, while it is true that an increase in the stock raises the marginal loss for being excluded, the increase in the stock should also increase the marginal gain from less competition should also increased. The two effects pull in opposite direction.

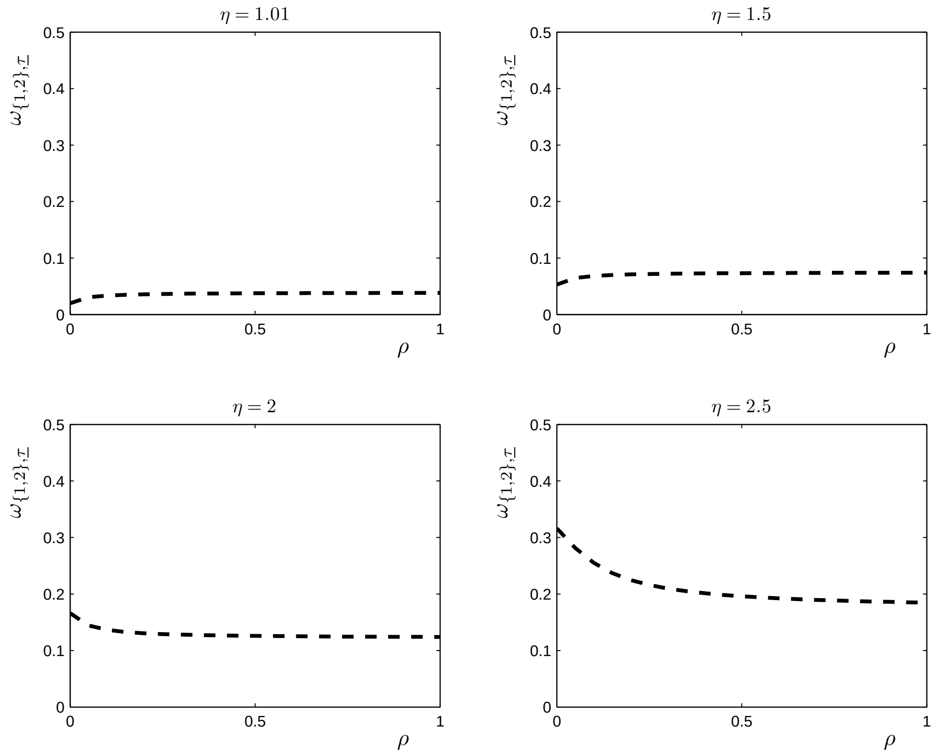

Figure 1: Effect of ρ on Optimal Extraction Rates under $\alpha = 0$

Specifically, as the elasticity of demand increases, the marginal benefit of extracting today raises, inducing a firm to extract more of the resource during the current period: it exacerbates the tragedy of the commons.[24] Therefore, in a situation of a strong tragedy of the commons (due to a high demand elasticity), the expected gain from less competition outweighs the expected loss from being expropriated, which decreases the present extraction of each firm at the equilibrium.

In the case of a low elasticity of demand, we obtain the opposite effect because the tragedy of the commons is weak. Indeed, the gain from facing less competition is not as significant compared to the loss of being excluded. The reasons is that a weak tragedy of the commons implies a weak dynamic externality between firms: remaining the only active firm does not signifi-

[24]See Koulovatianos and Mirman (2007) for the role of the elasticity of demand regarding the effect of externalities on the behavior of the firms for such a dynamic problem.

cantly increase profit (relatively to the other situation) since the externality was weak to begin with. Thus, the marginal loss of being excluded is eventually higher than the marginal gain of staying the only firm in the future, and present extraction of both firms increases at the equilibrium. These are the mechanisms at work behind Figure 1.

A final comment is in order. To analyze the effect of ownership risk in a common resource extraction problem, we have assumed that the two firms face the same demand elasticity. As the elasticity of demand is key in determining the influence of ownership risk on extraction, we discuss the case of different elasticities of demand. To simplify the discussion, we normalize the cost of extraction rights to zero. Details of the extension of the model to different demand elasticities are relegated to Appendix B. Figures 2 and 3 show that our results are robust to different elasticities of demand. In particular, Figure 2 provides information about the effect of an increase in the probability of exclusion on the extraction rate of firm 1, ω_1. Specifically, it shows a contour plot of the derivative of the extraction rate of firm 1 with respect to ρ. An increase in the elasticity of demand in the market supplied by firm 1 unambiguously decreases the extraction rate of firm 1. The effect of η_2 on the extraction rate of firm 1 is ambiguous. For low values of η_1, an increase in η_2 increases the extraction rate of firm 1. For high values of η_1, an increase in η_2 decreases the extraction rate of firm 1. While Figure 2 isolates the influence of the elasticities of demand on one firm, Figure 3 provides a general view of the effect of the demand elasticities on the overall extraction rate, $\omega_1 + \omega_2$. Consistent with our previous discussion, higher values of elasticities of demand imply a negative effect of the risk of exclusion on the overall extraction rate.

4 Final Remarks

In this paper, ownership risk is shown to have an ambiguous effect on extraction in a common-resource dynamic game. In particular, if ownership risk includes a risk of expropriation in which the identities of the excluded firms are unknown *ex ante*, then the present extraction of all the firms may decrease along with a higher risk of expropriation. The elasticity of demand for the resource is key in explaining the effect of ownership risk on present extraction. While we have adopted a specific form to study the ambiguous effect of ownership risk on present extraction, the intuition behind our main result seems to be quite robust.

We now discuss some of our assumptions. First, we have ignored the interaction of the two firms in the market. Focusing on the dynamic interaction only (through the extraction of the resource) allows for a clearer statement of the mechanism at work. In fact, introducing a duopolistic market increases the magnitude of the effect of ownership risk on present extraction behavior. To see this, we provide a formal treatment in Appendix C. Specifically, Figure 4 shows the effect of ownership risk on extraction for both monopoly and duopoly in the resale market. The dotted line refers to the monopoly case, as in the body of the paper. The solid line refers to duopoly in the resale market. From Figure 4, the interaction between both firms in the resale market reinforces the negative effect of ownership risk on present extraction rates. Indeed, in the case of both market and dynamic externalities, the threat of excluding one firm weakens competition not only in the extraction of the resource, but also in the sale of the resource. Hence, adding strategic interaction in the resale market increases the expected gain from less competition. Moreover, from Figure 4, the extraction rate always decreases with the risk of expropriation, irrespective of the elasticity of the demand. The reason is that the gain of being alone in both extracting *and* selling the resource outweighs the loss of being excluded even for small values of demand elasticity. Interestingly, for high values of the elasticity of demand and the likelihood of risk of expropriation, the extraction rate of a duopoly converges to the extraction rate of our benchmark monopoly, i.e., two firms interacting in the resale market may become almost as conservative as two monopolies.[25]

Second, we have assumed that the remaining firm cannot capture the market of the excluded firm. Suppose it could, then the ambiguous effect

[25] A perfectly competitive resale market would strengthen the tragedy of the commons as firms extract more in the present. Consistent with our explanation, a strong tragedy of the commons (due to perfect competition) should imply an extraction rate that is decreasing with the risk of exclusion.

would remain because the benefit from facing less competition would be further enhanced, i.e., future profits would come from two markets instead of one in the case of the other firm being excluded.

Third, the assumption of a one-time change is merely for simplicity. The ambiguity of the effect of ownership risk on extraction is likely to remain and is not necessarily weakened if the agreement is subject to more changes, i.e., with a richer structure of ownership risk. Indeed, while the gains of facing less competition might be reduced (as there would still exist a threat of subsequent exclusions), the loss from being excluded the first time should also be reduced since the presently excluded firm could also have the possibility of being allowed back to extract the resource in future. In the same vein, we can think of a situation in which only one firm is under the threat of expropriation, e.g., a foreign firm competing with a safe domestic firm. If both firms know that the foreign firm may be expropriated, then the domestic firm should be more conservative in its extraction rate (because it may become a monopoly in the future), while the foreign firm should extract at a quick pace in the present period, so as to rip benefits as quickly as possible. The main result of the paper may hold if the conservative effect of the domestic firm overcomes the higher extraction of the foreign firm. Using richer structures of ownership risk to study the effect of ownership risk on extraction would be very interesting for future research.

Fourth, we study the relationship between ownership risk and extraction behavior in an economy with only two firms. Adding more firms alters this relationship depending on the type of risk the firms faced. The results will then depend on the initial number of firms and the relative size of the group to be excluded. For instance, if a large number of firm are at risk of being excluded, then it will have a strong effect on both the marginal loss of being excluded as well as the marginal gain of facing less competition, and our results are very likely to hold. However, if many firms are present to extract the resource, but only one of them is at risk to be excluded, then an increase in ownership risk should have a minimal impact on both the marginal loss of being excluded and the marginal gain of facing less competition, and, in turn, should lead to a small change in extraction behavior.

Finally, we consider an exogenous agreement. Our purpose was to show that there exists types of agreement leading to an ambiguous effect of ownership risk on extraction behavior. Whether these agreements and changes are the ones a government would implement to achieve a particular objective such as avoiding the tragedy of the commons was outside the scope of this paper, but is certainly important work for future research. Indeed, if we modeled how the government decides the timing and the identities of the excluded firms, then ownership risk would be endogenized. While we show that ownership risk can have an ambiguous impact for a wide range of probabilities of ownership risk (the pair of α and ρ), it would be interesting to study whether the interaction of the government with the firms would yield ownership risk, which, in turn, would induce firms to reduce extraction. This is likely possible if the government needs to contract with several firms (capacity constraints on the part of the firm), but is concerned with reducing the tragedy of the commons.

A Proofs

Proof of Proposition 2.4. We first derive the value functions and strategies corresponding to (4), after the change in the agreement. In order to combine the three cases $\{\mathcal{F},\tau\} = \{\{1,2\},\overline{\tau}\}$, $\{\mathcal{F},\tau\} = \{\{j\},\underline{\tau}\}$, and $\{\mathcal{F},\tau\} = \{\{j\},\overline{\tau}\}$, we solve the problem for $N \in \{1,2\}$ symmetric firms. Plugging the conjecture $V_j(y,\mathcal{F},\tau) = \varphi_{\mathcal{F},\tau} y^{1-\frac{1}{\eta}}$ into (4) yields

$$V_j(y,\mathcal{F},\tau) = \max_{q_j} \; 1_{[j\in\mathcal{F}]}(1-\tau)q_j^{1-\frac{1}{\eta}} + \delta\varphi_{\mathcal{F},\tau}\left(y - \sum\nolimits_{k=1}^{N} q_k\right)^{1-\frac{1}{\eta}}. \tag{10}$$

The corresponding first-order condition is

$$\left(1-\frac{1}{\eta}\right)(1-\tau)q_j^{-\frac{1}{\eta}} - \left(1-\frac{1}{\eta}\right)\delta\varphi_{\mathcal{F},\tau}\left(y-\sum\nolimits_{k=1}^{N} q_k\right)^{-\frac{1}{\eta}} = 0, \tag{11}$$

so that, given the conjecture, the symmetric Cournot-Nash solution is

$$g(y,\mathcal{F},\tau) = \omega_{\mathcal{F},\tau} y, \tag{12}$$

where

$$\omega_{\mathcal{F},\tau} = \frac{(1-\tau)^{\eta}}{(1-\tau)^{\eta}N + \delta^{\eta}\varphi_{\mathcal{F},\tau}^{\eta}}. \tag{13}$$

Plugging (12) into the objective function of (10) yields

$$V_j(y,\mathcal{F},\tau) = \left((1-\tau)\omega_{\mathcal{F},\tau}^{1-\frac{1}{\eta}} + \delta\varphi_{\mathcal{F},\tau}(1-N\omega_{\mathcal{F},\tau})^{1-\frac{1}{\eta}}\right) y^{1-\frac{1}{\eta}}, \tag{14}$$

$$\equiv \varphi_{\mathcal{F},\tau} y^{1-\frac{1}{\eta}}, \tag{15}$$

so that

$$\varphi_{\mathcal{F},\tau} = \frac{(1-\tau)\omega_{\mathcal{F},\tau}^{1-\frac{1}{\eta}}}{1-\delta(1-N\omega_{\mathcal{F},\tau})^{1-\frac{1}{\eta}}}, \tag{16}$$

where $\omega_{\mathcal{F},\tau}$ is defined by (13). Here, (13) and (16) characterize $\omega_{\mathcal{F},\tau}$. Specifically, solving (13) for $\varphi_{\mathcal{F},\tau}$ yields

$$\varphi_{\mathcal{F},\tau} = \frac{1-\tau}{\delta}(1-N\omega_{\mathcal{F},\tau})^{\frac{1}{\eta}}\omega_{\mathcal{F},\tau}^{-\frac{1}{\eta}}. \tag{17}$$

Therefore, equating expressions (16) and (17) yields an implicit characterization of $\omega_{\mathcal{F},\tau} \in (0, 1/N)$, i.e.,

$$\delta + \delta(1 - N)\omega_{\mathcal{F},\tau} = (1 - N\omega_{\mathcal{F},\tau})^{\frac{1}{\eta}}. \tag{18}$$

Plotting the left and right-hand sides of (18) shows that $\omega_{\mathcal{F},\tau} \in (0, 1/N)$ exists and is unique, which implies that (16) is unique and the conjecture of the value function is correct. Moreover, the second-order condition holds. Therefore, for $\{\mathcal{F}, \tau\} = \{\{1, 2\}, \overline{\tau}\}$, $\{\mathcal{F}, \tau\} = \{\{j\}, \underline{\tau}\}$, and $\{\mathcal{F}, \tau\} = \{\{j\}, \overline{\tau}\}$, the value function and the optimal strategy are defined by (5) and (6), respectively.

Having derived the value functions under the new agreement, we can now derive the value function corresponding to (3), prior to the change in the agreement, i.e., $\{\mathcal{F}, \tau\} = \{\{1, 2\}, \underline{\tau}\}$. Plugging into (3) the conjecture $V_j(y, \{1, 2\}, \underline{\tau}) = \varphi_{\{1,2\},\underline{\tau}} y^{1-\frac{1}{\eta}}$ and the known value function $V_j(y, \mathcal{F}, \tau)$ corresponding to (4) yields

$$\begin{aligned} V_j(y, \{1, 2\}, \underline{\tau}) = &\max_{q_j} \; (1 - \underline{\tau}) q_j^{1-\frac{1}{\eta}} + \delta(1 - \rho)(1 - \alpha)\varphi_{\{1,2\},\underline{\tau}}(y - q_j - q_k)^{1-\frac{1}{\eta}} \\ &+ \delta(1 - \rho)\alpha\varphi_{\{1,2\},\overline{\tau}}(y - q_j - q_k)^{1-\frac{1}{\eta}} + \delta\rho(1 - \alpha)\varphi_{\{j\},\underline{\tau}}(y - q_j - q_k)^{1-\frac{1}{\eta}}/2 \\ &+ \delta\rho\alpha\varphi_{\{j\},\overline{\tau}}(y - q_j - q_k)^{1-\frac{1}{\eta}}/2, \end{aligned} \tag{19}$$

where $\varphi_{\{1,2\},\underline{\tau}}$ is unknown at this point, but $\varphi_{\{1,2\},\overline{\tau}}$, $\varphi_{\{j\},\underline{\tau}}$, and $\varphi_{\{j\},\overline{\tau}}$ are known constants. Taking the first-order condition and rearranging yields

$$\begin{aligned} (1 - \underline{\tau}) q_j^{-\frac{1}{\eta}} = \delta \big[&(1 - \rho)(1 - \alpha)\varphi_{\{1,2\},\underline{\tau}} + (1 - \rho)\alpha\varphi_{\{1,2\},\overline{\tau}} \\ &+ \rho(1 - \alpha)\varphi_{\{j\},\underline{\tau}}/2 + \rho\alpha\varphi_{\{j\},\overline{\tau}}/2\big] (y - q_j - q_k)^{-\frac{1}{\eta}}, \end{aligned} \tag{20}$$

so that, given the conjecture, the symmetric Cournot-Nash solution is

$$g(y, \{1, 2\}, \underline{\tau}) = \omega_{\{1,2\},\underline{\tau}} y. \tag{21}$$

Here,

$$\omega_{\{1,2\},\underline{\tau}} = \frac{(1 - \underline{\tau})^\eta}{2(1 - \underline{\tau})^\eta + \delta^\eta((1 - \rho)(1 - \alpha)\varphi_{\{1,2\},\underline{\tau}} + \Delta)^\eta}, \tag{22}$$

where

$$\Delta = (1-\rho)\alpha\varphi_{\{1,2\},\overline{\tau}} + \rho(1-\alpha)\varphi_{\{j\},\underline{\tau}}/2 + \rho\alpha\varphi_{\{j\},\overline{\tau}}/2 \tag{23}$$

is known. Plugging (21) into the objective function of (19) yields

$$\begin{aligned} V_j(y,\{1,2\},\underline{\tau}) =& \big((1-\underline{\tau})\omega_{\{1,2\},\underline{\tau}}^{1-\frac{1}{\eta}} \\ &+ \delta((1-\rho)(1-\alpha)\varphi_{\{1,2\},\underline{\tau}} + \Delta)(1-2\omega_{\{1,2\},\underline{\tau}})^{1-\frac{1}{\eta}}\big)y^{1-\frac{1}{\eta}}, \end{aligned} \tag{24}$$

$$\equiv \varphi_{\{1,2\},\underline{\tau}}y^{1-\frac{1}{\eta}}, \tag{25}$$

so that

$$\varphi_{\{1,2\},\underline{\tau}} = \frac{(1-\underline{\tau})\omega_{\{1,2\},\underline{\tau}}^{1-\frac{1}{\eta}} + \delta\Delta(1-2\omega_{\{1,2\},\underline{\tau}})^{1-\frac{1}{\eta}}}{1-\delta(1-\rho)(1-\alpha)(1-2\omega_{\{1,2\},\underline{\tau}})^{1-\frac{1}{\eta}}}, \tag{26}$$

where $\omega_{\{1,2\},\underline{\tau}}$ is defined by (22). Here, (22) and (26) characterize $\omega_{\{1,2\},\underline{\tau}}$. Specifically, solving (22) for $\varphi_{\{1,2\},\underline{\tau}}$ yields

$$\varphi_{\{1,2\},\underline{\tau}} = \frac{1-\underline{\tau}}{\delta(1-\rho)(1-\alpha)}(1-2\omega_{\{1,2\},\underline{\tau}})^{\frac{1}{\eta}}\omega_{\{1,2\},\underline{\tau}}^{-\frac{1}{\eta}} - \frac{\Delta}{(1-\rho)(1-\alpha)}. \tag{27}$$

Therefore, equating expressions (26) and (27) yields an implicit characterization of $\omega_{\{1,2\},\underline{\tau}} \in (0,1/2)$, i.e.,

$$\begin{aligned} \frac{(1-\underline{\tau})\omega_{\{1,2\},\underline{\tau}}^{1-\frac{1}{\eta}} + \delta\Delta(1-2\omega_{\{1,2\},\underline{\tau}})^{1-\frac{1}{\eta}}}{1-\delta(1-\rho)(1-\alpha)(1-2\omega_{\{1,2\},\underline{\tau}})^{1-\frac{1}{\eta}}} =& \frac{1-\underline{\tau}}{\delta(1-\rho)(1-\alpha)}(1-2\omega_{\{1,2\},\underline{\tau}})^{\frac{1}{\eta}}\omega_{\{1,2\},\underline{\tau}}^{-\frac{1}{\eta}} \\ &- \frac{\Delta}{(1-\rho)(1-\alpha)} \end{aligned} \tag{28}$$

or

$$\delta(1-\rho)(1-\alpha)(1-\underline{\tau})(1-\omega_{\{1,2\},\underline{\tau}}) + \delta\Delta\omega_{\{1,2\},\underline{\tau}}^{\frac{1}{\eta}} = (1-\underline{\tau})(1-2\omega_{\{1,2\},\underline{\tau}})^{\frac{1}{\eta}}, \tag{29}$$

where Δ is defined by (23). Plotting the left and right-hand sides of (29) shows that $\omega_{\{1,2\},\underline{\tau}} \in (0,1/2)$ exists and is unique, which implies that (26) is unique and that the conjecture of the value function is correct. Moreover, the second-order condition holds. Therefore, for $\{\mathcal{F},\tau\} = \{\{1,2\},\underline{\tau}\}$, the value function and the optimal strategy are defined by (5) and (6), respectively.

Proof of Proposition 3.2. Since $g(y, \{1,2\}, \underline{\tau}) = \omega_{\{1,2\},\underline{\tau}} y$, it is enough to calculate the derivative of $\omega_{\{1,2\},\underline{\tau}}$ with respect to α, $\overline{\tau}$, and $\underline{\tau}$. If $\rho = 0$ and $\alpha \geq 0$, then, from (8), (23), and (29), $\omega_{\{1,2\},\underline{\tau}}$ is implicitly defined by

$$\delta(1-\alpha)(1-\omega_{\{1,2\},\underline{\tau}}) + \delta\alpha \frac{\frac{1-\overline{\tau}}{1-\underline{\tau}} \omega_{\{1,2\},\overline{\tau}}^{1-\frac{1}{\eta}}}{1-\delta(1-2\omega_{\{1,2\},\overline{\tau}})^{1-\frac{1}{\eta}}} \omega_{\{1,2\},\underline{\tau}}^{\frac{1}{\eta}} = (1-2\omega_{\{1,2\},\underline{\tau}})^{\frac{1}{\eta}}, \tag{30}$$

where, using (18), $\omega_{\{1,2\},\overline{\tau}}$ is implicitly defined by

$$\delta(1-\omega_{\{1,2\},\overline{\tau}}) = (1-2\omega_{\{1,2\},\overline{\tau}})^{\frac{1}{\eta}}. \tag{31}$$

Here, the left-hand side of (30) is increasing in $\omega_{\{1,2\},\underline{\tau}}$ and the right-hand side of (30) is decreasing in $\omega_{\{1,2\},\underline{\tau}}$. First, the derivative of the left-hand side of (30) with respect to α is

$$-\delta(1-\omega_{\{1,2\},\underline{\tau}}) + \delta \frac{\frac{1-\overline{\tau}}{1-\underline{\tau}} \omega_{\{1,2\},\overline{\tau}}^{1-\frac{1}{\eta}}}{1-\delta(1-2\omega_{\{1,2\},\overline{\tau}})^{1-\frac{1}{\eta}}} \omega_{\{1,2\},\underline{\tau}}^{\frac{1}{\eta}} < 0, \tag{32}$$

which is always negative for $\omega_{\{1,2\},\underline{\tau}} \in [0, 1/2]$. Thus, the left-hand side of (30) decreases in α, implying that $\omega_{\{1,2\},\underline{\tau}}$ increases in α. Second, if $\overline{\tau}$ increases, then the left-hand side of (30) decreases, implying that $\omega_{\{1,2\},\underline{\tau}}$ increases in $\overline{\tau}$. Finally, if $\underline{\tau}$ increases, then the left-hand side of (30) increases, implying that $\omega_{\{1,2\},\underline{\tau}}$ decreases in $\underline{\tau}$.

B Different Demand Elasticities

We now consider the case of different demand elasticity, i.e., $\eta_1 \neq \eta_2$. To simplify the discussion, we normalize the cost of extraction rights to zero.

Hence, analogous to (3), the value function of firm j is

$$V_j(y,\{1,2\}) = \max_{q_j} q_j^{1-\frac{1}{\eta_j}} + \delta(1-\rho)V_j(y-q_j-q_k,\{1,2\}) \\ + \delta\rho V_j(y-q_j-q_k,\{j\})/2, \tag{33}$$

where

$$V_j(y,\{j\}) = \max_{q_j} q_j^{1-\frac{1}{\eta_j}} + \delta V_j(y-q_j,\{j\}), \\ = (1-\delta^{\eta_j})^{-\frac{1}{\eta_j}} y^{1-\frac{1}{\eta_j}}. \tag{34}$$

The conjecture for (33) is $V_j(y,\{1,2\}) = \varphi_j y^{1-\frac{1}{\eta_j}}$, $\varphi_j > 0$. Plugging the conjecture and (34) into (33) yields

$$V_j(y,\{1,2\}) = \max_{q_j} q_j^{1-\frac{1}{\eta_j}} + \delta(1-\rho)\varphi_j(y-q_j-q_k)^{1-\frac{1}{\eta_j}} \\ + \delta\rho(1-\delta^{\eta_j})^{-\frac{1}{\eta_j}}(y-q_j-q_k)^{1-\frac{1}{\eta_j}}/2. \tag{35}$$

Taking the first-order condition and rearranging yields

$$q_j^{-\frac{1}{\eta_j}} = \delta\left((1-\rho)\varphi_j + \rho(1-\delta^{\eta_j})^{-\frac{1}{\eta_j}}/2\right)(y-q_j-q_k)^{-\frac{1}{\eta_j}}, \tag{36}$$

so that, given the conjecture, the Cournot-Nash solution is

$$g_j(y,\{1,2\}) = \omega_j y, \tag{37}$$

where, from (36),

$$\omega_j = \frac{1-\omega_k}{1+\delta^{\eta_j}\left((1-\rho)\varphi_j + \rho(1-\delta^{\eta_j})^{-\frac{1}{\eta_j}}/2\right)^{\eta_j}}. \tag{38}$$

Solving (38) for φ_j yields

$$\varphi_j = \frac{(1-\omega_j-\omega_k)^{\frac{1}{\eta_j}}}{\omega_j^{\frac{1}{\eta_j}}\delta(1-\rho)} - \frac{\rho(1-\delta^{\eta_j})^{-\frac{1}{\eta_j}}}{2(1-\rho)}. \tag{39}$$

Next, plugging (37) into the objective function of (35) yields

$$\begin{aligned} V_j(y,\{1,2\}) =& \Big(\omega_j^{1-\frac{1}{\eta_j}} + \delta(1-\rho)\varphi_j(1-\omega_j-\omega_k)^{1-\frac{1}{\eta_j}} \\ &+ \delta\rho(1-\delta^{\eta_j})^{-\frac{1}{\eta_j}}(1-\omega_j-\omega_k)^{1-\frac{1}{\eta_j}}/2\Big)y^{1-\frac{1}{\eta_j}}, \qquad (40)\\ \equiv& \varphi_j y^{1-\frac{1}{\eta_j}}, \qquad (41) \end{aligned}$$

so that

$$\varphi_j = \frac{\omega_j^{1-\frac{1}{\eta_j}} + \delta\rho(1-\delta^{\eta_j})^{-\frac{1}{\eta_j}}(1-\omega_j-\omega_k)^{1-\frac{1}{\eta_j}}/2}{1-\delta(1-\rho)(1-\omega_j-\omega_k)^{1-\frac{1}{\eta_j}}}. \tag{42}$$

Combining (39) and (42) for $j=1,2$ yields a nonlinear system in ω_1 and ω_2:

$$\frac{(1-\omega_1-\omega_2)^{\frac{1}{\eta_1}}}{\omega_1^{\frac{1}{\eta_1}}\delta(1-\rho)} - \frac{\rho(1-\delta^{\eta_1})^{-\frac{1}{\eta_1}}}{2(1-\rho)} = \frac{\omega_1^{1-\frac{1}{\eta_1}} + \delta\rho(1-\delta^{\eta_1})^{-\frac{1}{\eta_1}}(1-\omega_1-\omega_2)^{1-\frac{1}{\eta_1}}/2}{1-\delta(1-\rho)(1-\omega_1-\omega_2)^{1-\frac{1}{\eta_1}}}, \tag{43}$$

and

$$\frac{(1-\omega_2-\omega_1)^{\frac{1}{\eta_2}}}{\omega_2^{\frac{1}{\eta_2}}\delta(1-\rho)} - \frac{\rho(1-\delta^{\eta_2})^{-\frac{1}{\eta_2}}}{2(1-\rho)} = \frac{\omega_2^{1-\frac{1}{\eta_2}} + \delta\rho(1-\delta^{\eta_2})^{-\frac{1}{\eta_2}}(1-\omega_2-\omega_1)^{1-\frac{1}{\eta_2}}/2}{1-\delta(1-\rho)(1-\omega_2-\omega_1)^{1-\frac{1}{\eta_2}}}. \tag{44}$$

Expressions (43) and (44) simplify to

$$2(1-\delta^{\eta_1})^{\frac{1}{\eta_1}}(1-\omega_1-\omega_2)^{\frac{1}{\eta_1}} - \delta\rho\omega_1^{\frac{1}{\eta_1}} = 2(1-\delta^{\eta_1})^{\frac{1}{\eta_1}}\delta(1-\rho)(1-\omega_2), \tag{45}$$

$$2(1-\delta^{\eta_2})^{\frac{1}{\eta_2}}(1-\omega_2-\omega_1)^{\frac{1}{\eta_2}} - \delta\rho\omega_2^{\frac{1}{\eta_2}} = 2(1-\delta^{\eta_2})^{\frac{1}{\eta_2}}\delta(1-\rho)(1-\omega_1). \tag{46}$$

Expressions (45) and (46) are solved to generate Figures 2 and 3. To generate the graphs, we set $\delta = 0.98$ and consider the cases of $\eta_1, \eta_2 \in [1.01, 3.5]$.

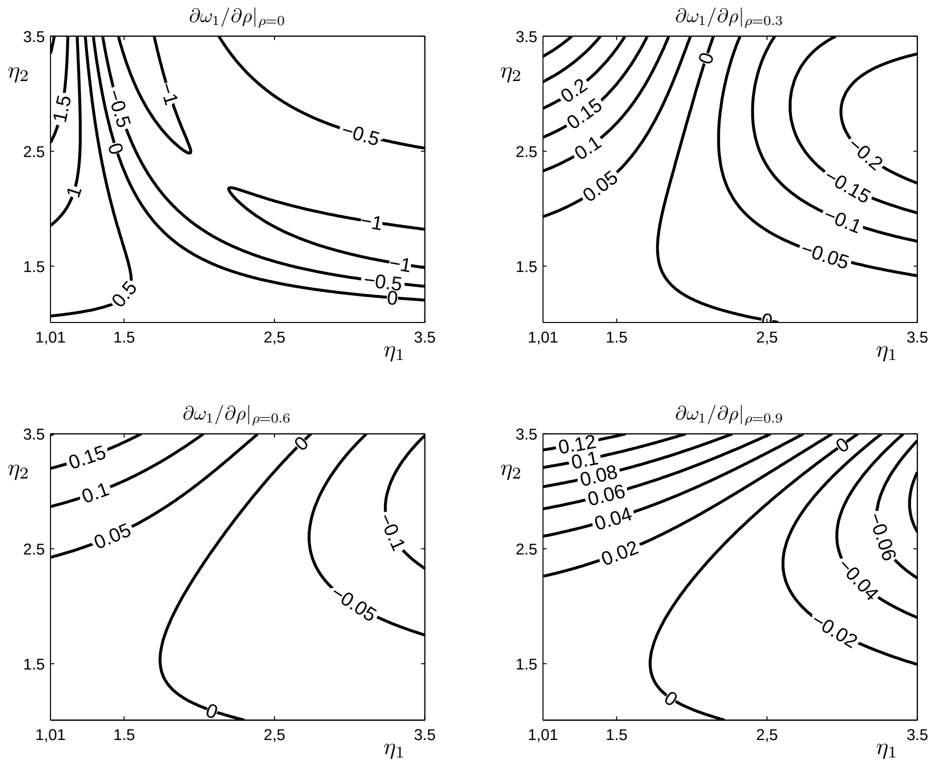

Figure 2: Contours of $\partial\omega_1^*/\partial\rho$

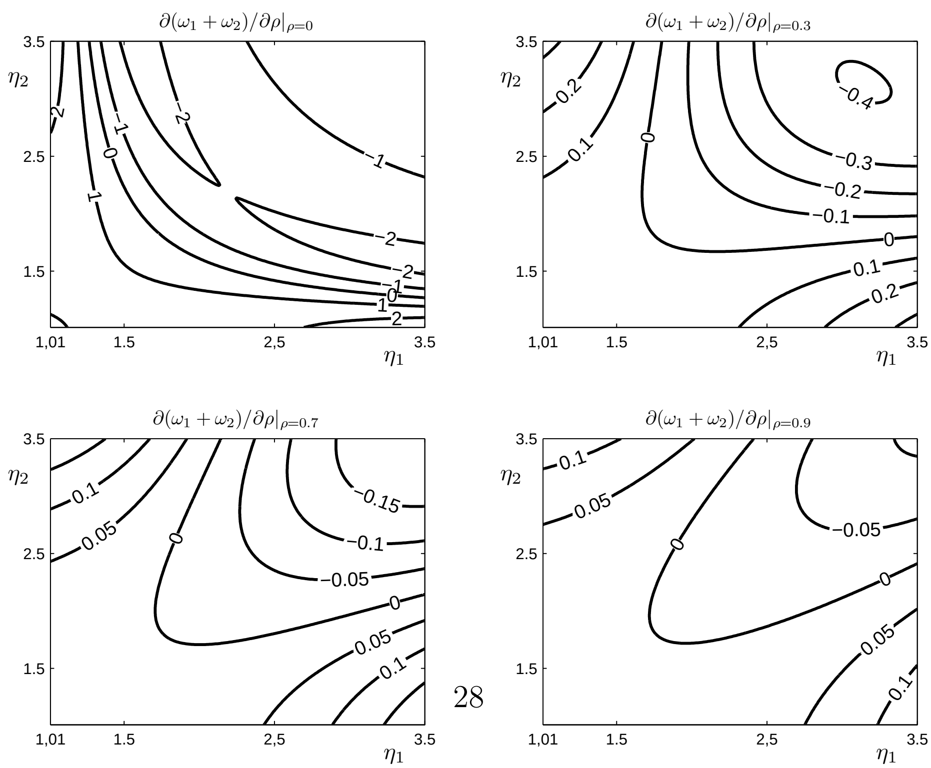

Figure 3: Contours of $\partial(\omega_1^* + \omega_2^*)/\partial\rho$

C Duopoly

We now study the effect of market structure by extending the benchmark monopoly model to duopoly. To simplify the discussion, we normalize the cost of extraction rights to zero. Hence, analogous to (3), the value function of firm j is

$$\begin{aligned} V_j(y,\{1,2\}) = &\max_{q_j} \gamma q_j^{1-\frac{1}{\eta}} + (1-\gamma)(q_j+q_k)^{-\frac{1}{\eta}} q_j + \delta(1-\rho)V_j(y-q_j-q_k,\{1,2\}) \\ &+ \delta\rho V_j(y-q_j-q_k,\{j\})/2, \end{aligned} \tag{47}$$

where $\gamma \in \{0,1\}$. Expression (47) combines the two cases at study, i.e., $\gamma = 1$ refers to monopoly while $\gamma = 0$ refers to duopoly. Using (7) evaluated at $\tau = 0$, it follows that

$$\begin{aligned} V_j(y,\{j\}) &= \max_{q_j} q_j^{1-\frac{1}{\eta}} + \delta V_j(y-q_j,\{j\}), \\ &= (1-\delta^\eta)^{-\frac{1}{\eta}} y^{1-\frac{1}{\eta}}. \end{aligned} \tag{48}$$

The conjecture for (47) is $V_j(y,\{1,2\}) = \varphi_D y^{1-\frac{1}{\eta}}$, $\varphi_D > 0$.[26] Plugging the conjecture and (48) into (47) yields

$$\begin{aligned} V_j(y,\{1,2\}) = &\max_{q_j} \gamma q_j^{1-\frac{1}{\eta}} + (1-\gamma)(q_j+q_k)^{-\frac{1}{\eta}} q_j + \delta(1-\rho)\varphi_D(y-q_j-q_k)^{1-\frac{1}{\eta}} \\ &+ \delta\rho(1-\delta^\eta)^{-\frac{1}{\eta}}(y-q_j-q_k)^{1-\frac{1}{\eta}}/2. \end{aligned} \tag{49}$$

The first-order condition corresponding to (49) is

$$\begin{aligned} &\gamma\left(1-\frac{1}{\eta}\right) q_j^{-\frac{1}{\eta}} + (1-\gamma)\left((q_j+q_k)^{-\frac{1}{\eta}} - \frac{1}{\eta}(q_j+q_k)^{-\frac{1}{\eta}-1} q_j\right) \\ &= \delta\left(1-\frac{1}{\eta}\right)\left((1-\rho)\varphi_D + \rho(1-\delta^\eta)^{-\frac{1}{\eta}}/2\right)(y-q_j-q_k)^{-\frac{1}{\eta}}, \end{aligned} \tag{50}$$

so that, given the conjecture, the symmetric Cournot-Nash solution is

$$g_D(y,\{1,2\}) = \omega_D y, \tag{51}$$

[26] The subscript D refers to *duopoly*.

where, from (50),

$$\omega_D = \frac{\left(\gamma\left(1-\frac{1}{\eta}\right)+(1-\gamma)2^{-\frac{1}{\eta}}\left(1-\frac{1}{2\eta}\right)\right)^{\eta}}{2\left(\gamma\left(1-\frac{1}{\eta}\right)+(1-\gamma)2^{-\frac{1}{\eta}}\left(1-\frac{1}{2\eta}\right)\right)^{\eta}+\delta^{\eta}\left(1-\frac{1}{\eta}\right)^{\eta}\left((1-\rho)\varphi_D+\rho(1-\delta^{\eta})^{-\frac{1}{\eta}}/2\right)^{\eta}}. \tag{52}$$

Solving (52) for φ_D yields

$$\varphi_D = \frac{(1-2\omega_D)^{\frac{1}{\eta}}\left(\gamma\left(1-\frac{1}{\eta}\right)+(1-\gamma)2^{-\frac{1}{\eta}}\left(1-\frac{1}{2\eta}\right)\right)}{\omega_D^{\frac{1}{\eta}}\delta\left(1-\frac{1}{\eta}\right)(1-\rho)} - \frac{\rho(1-\delta^{\eta})^{-\frac{1}{\eta}}}{2(1-\rho)}. \tag{53}$$

Next, plugging (51) into the objective function of (47) yields

$$\begin{aligned} V_j(y,\{1,2\}) &= \left(\gamma\omega_D^{1-\frac{1}{\eta}}+(1-\gamma)2^{-\frac{1}{\eta}}\omega_D^{1-\frac{1}{\eta}}+\delta(1-\rho)\varphi_D(1-2\omega_D)^{1-\frac{1}{\eta}}\right. \\ &\quad \left.+\delta\rho(1-\delta^{\eta})^{-\frac{1}{\eta}}(1-2\omega_D)^{1-\frac{1}{\eta}}/2\right)y^{1-\frac{1}{\eta}}, \qquad (54) \\ &\equiv \varphi_D y^{1-\frac{1}{\eta}}, \qquad (55) \end{aligned}$$

so that

$$\varphi_D = \frac{\gamma\omega_D^{1-\frac{1}{\eta}}+(1-\gamma)2^{-\frac{1}{\eta}}\omega_D^{1-\frac{1}{\eta}}+\delta\rho(1-\delta^{\eta})^{-\frac{1}{\eta}}(1-2\omega_D)^{1-\frac{1}{\eta}}/2}{1-\delta(1-\rho)(1-2\omega_D)^{1-\frac{1}{\eta}}}. \tag{56}$$

Combining (53) and (56) yields an implicit solution for ω_D:

$$\begin{aligned} &\frac{(1-2\omega_D)^{\frac{1}{\eta}}\left(\gamma\left(1-\frac{1}{\eta}\right)+(1-\gamma)2^{-\frac{1}{\eta}}\left(1-\frac{1}{2\eta}\right)\right)}{\omega_D^{\frac{1}{\eta}}\delta\left(1-\frac{1}{\eta}\right)(1-\rho)} - \frac{\rho(1-\delta^{\eta})^{-\frac{1}{\eta}}}{2(1-\rho)} \\ &= \frac{\gamma\omega_D^{1-\frac{1}{\eta}}+(1-\gamma)2^{-\frac{1}{\eta}}\omega_D^{1-\frac{1}{\eta}}+\delta\rho(1-\delta^{\eta})^{-\frac{1}{\eta}}(1-2\omega_D)^{1-\frac{1}{\eta}}/2}{1-\delta(1-\rho)(1-2\omega_D)^{1-\frac{1}{\eta}}}. \qquad (57) \end{aligned}$$

When $\gamma = 1$, expression (57) simplifies to

$$2(1-2\omega_D)^{\frac{1}{\eta}} = 2\delta(1-\rho)(1-\omega_D)+\delta\rho(1-\delta^{\eta})^{-\frac{1}{\eta}}\omega_D^{\frac{1}{\eta}}. \tag{58}$$

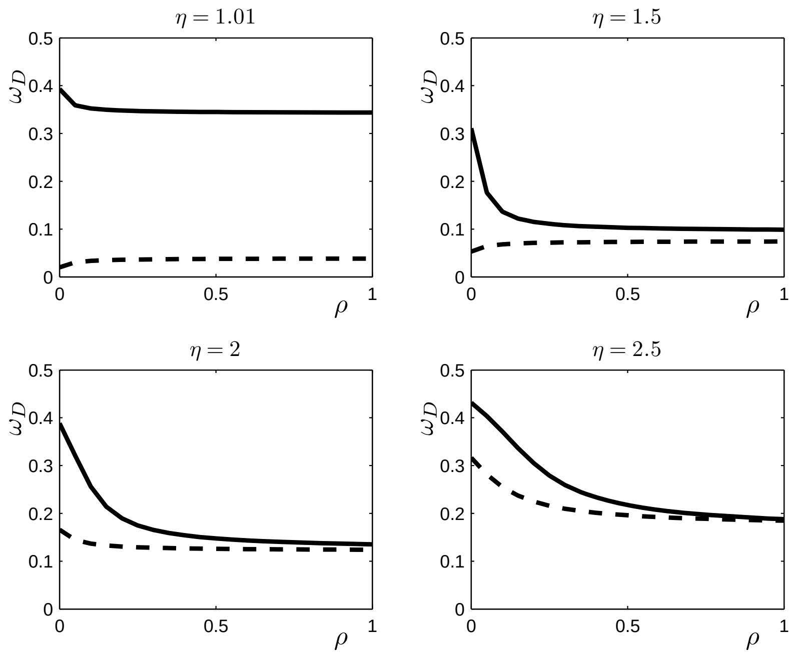

Figure 4: Comparison between Monopoly and Duopoly

When $\gamma = 0$, expression (57) simplifies to

$$2^{1-\frac{1}{\eta}}\left(1-\frac{1}{2\eta}\right)(1-2\omega_D)^{\frac{1}{\eta}}$$
$$= 2^{1-\frac{1}{\eta}}\delta(1-\rho)\left(1-\frac{1}{2\eta}-\omega_D\right)+\delta\rho\left(1-\frac{1}{\eta}\right)(1-\delta^{\eta})^{-\frac{1}{\eta}}\omega_D^{\frac{1}{\eta}}. \qquad (59)$$

Expressions (58) and (59) are solved to generate Figure 4.[27] Specifically, Figure 4 provide the effect of ownership risk on extraction for both monopoly and duopoly in the resale market. The dotted line refers to the monopoly case, as in the body of the paper. The solid line refers to duopoly in the resale market.

[27] To generate the graphs, we set $\delta = 0.98$, and consider the cases of $\eta \in \{1.01, 1.5, 2, 2.5\}$ and $\rho \in [0, 1]$.

D Figures

Figures 5, 6, 7, and 8 provide a contour plot of the extraction rate $\omega_{\{1,2\},\underline{T}}$ of the stock exploited under the initial agreement for all possible values of ρ and α, and under different values of the elasticity of demand ($\eta = \{1.01, 1.5, 2, 2.5\}$) and the cost of extraction rights. Specifically, given a specific elasticity of demand and cost of extraction rights, a graph represents the different extraction rates chosen by a firm under different risky situations, i.e., different pairs of ρ and α. A curve in the graph reads similarly as an indifference curve in a utility graph: it represents the set of probabilities yielding the same extraction rate. The relative bending of the curves provides information about the marginal rate of substitution or complementarity between the risk of a higher cost of extraction rights and the risk of exclusion. If a curve is downward sloping, it means that the extraction rate is increasing in both sources of risk: in order to keep the same extraction rate, one should diminish one risk to compensate for the increase in the other risk. If a curve is upward sloping, it means that the probability of being expropriated leads to a lower extraction rate, while the risk of being more taxed in the future has the opposite effect, i.e., extraction rate is increased. The more bent a curve is, the stronger the substitution or complementarity patterns are.

Figures 9, 10, 11, and 12 isolates the effect of the risk of a higher cost of extraction rights on the present extraction rate.

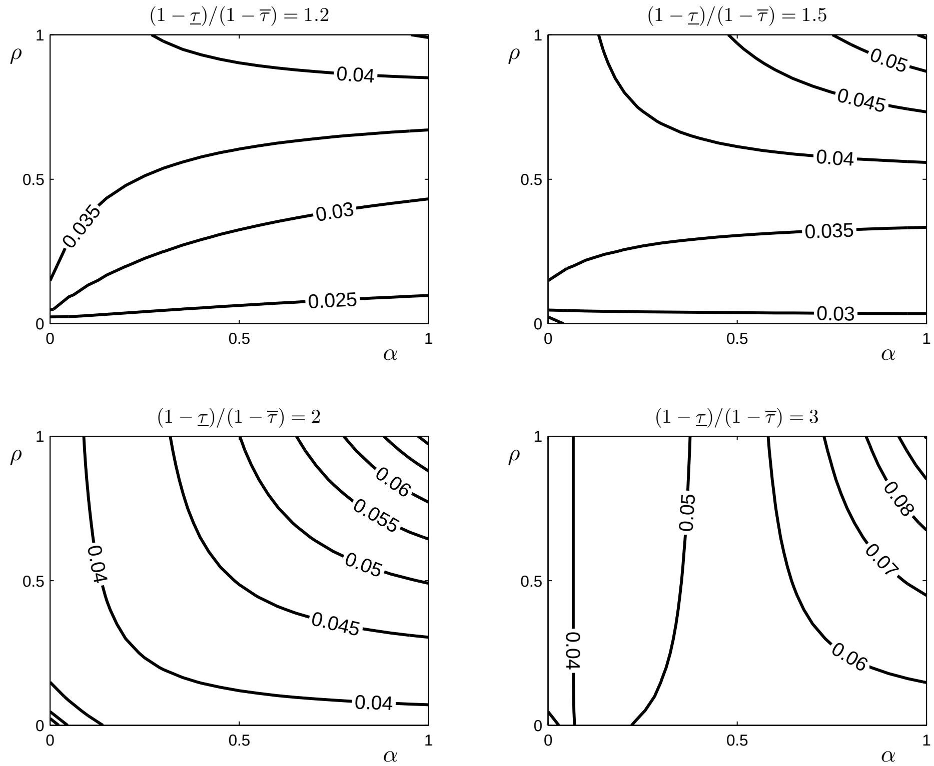

Figure 5: Contours of Optimal Extraction Rates under $\eta = 1.01$

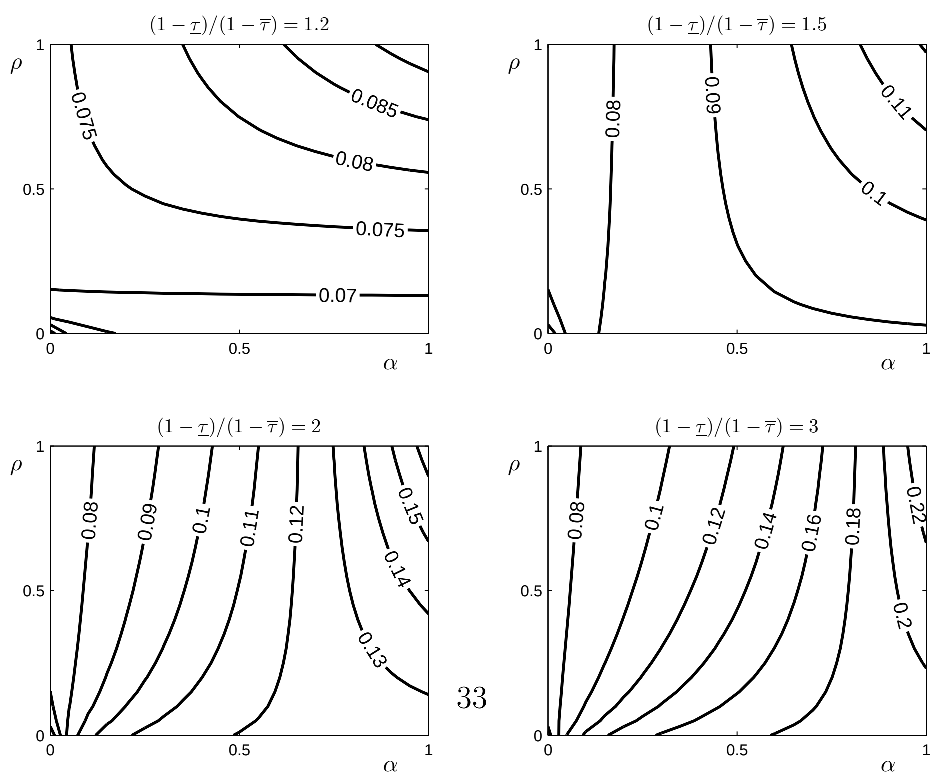

Figure 6: Contours of Optimal Extraction Rates under $\eta = 1.5$

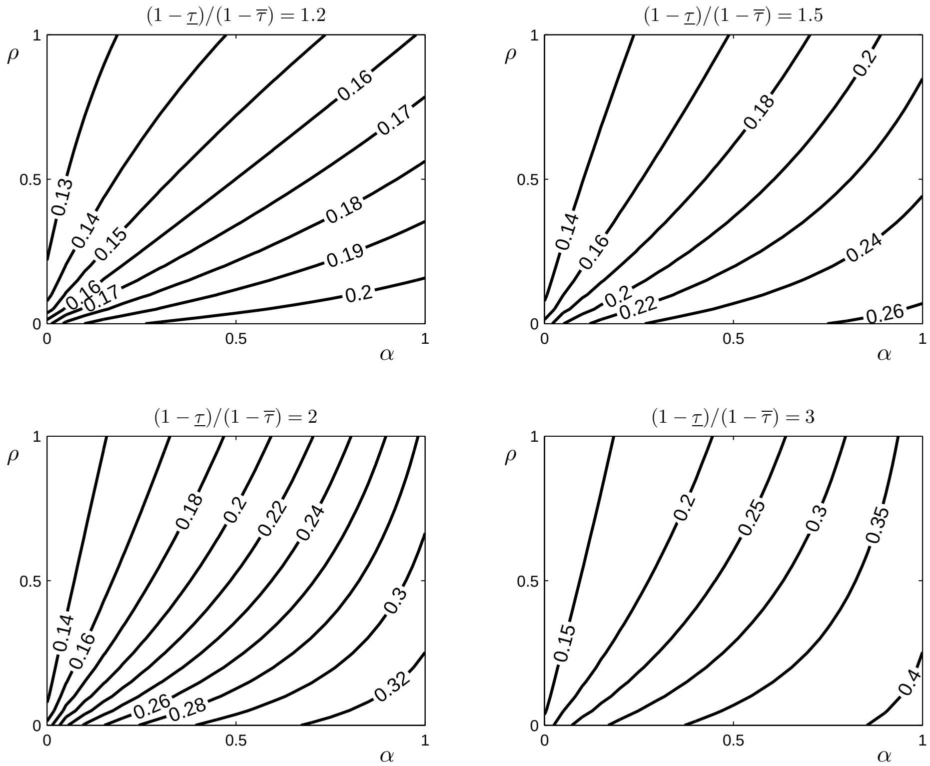

Figure 7: Contours of Optimal Extraction Rates under $\eta = 2$

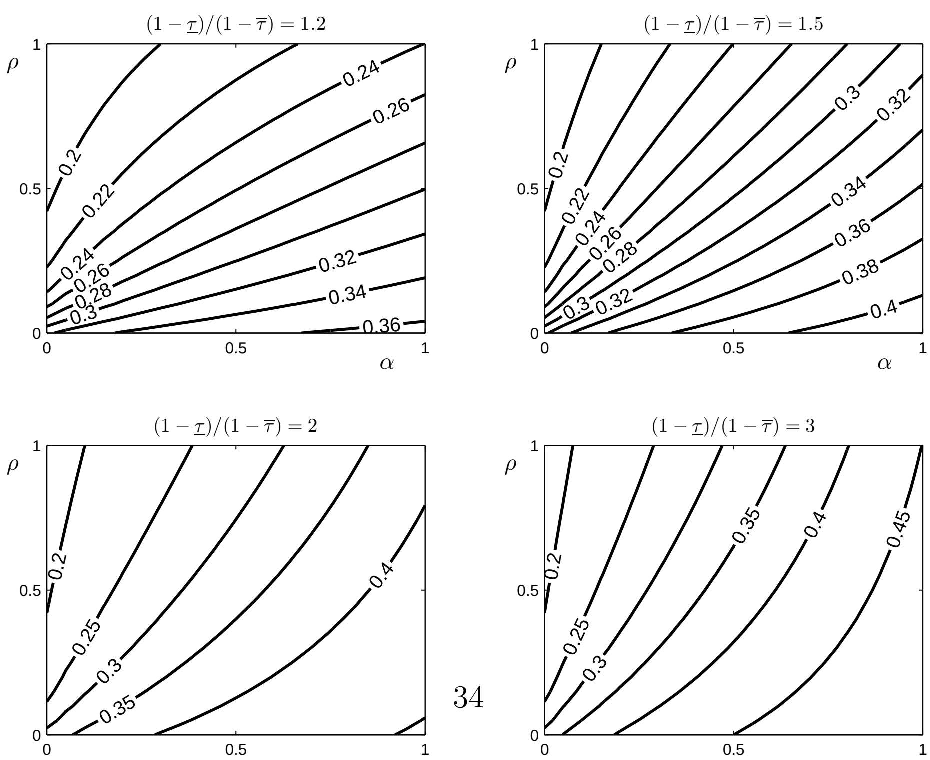

Figure 8: Contours of Optimal Extraction Rates under $\eta = 2.5$

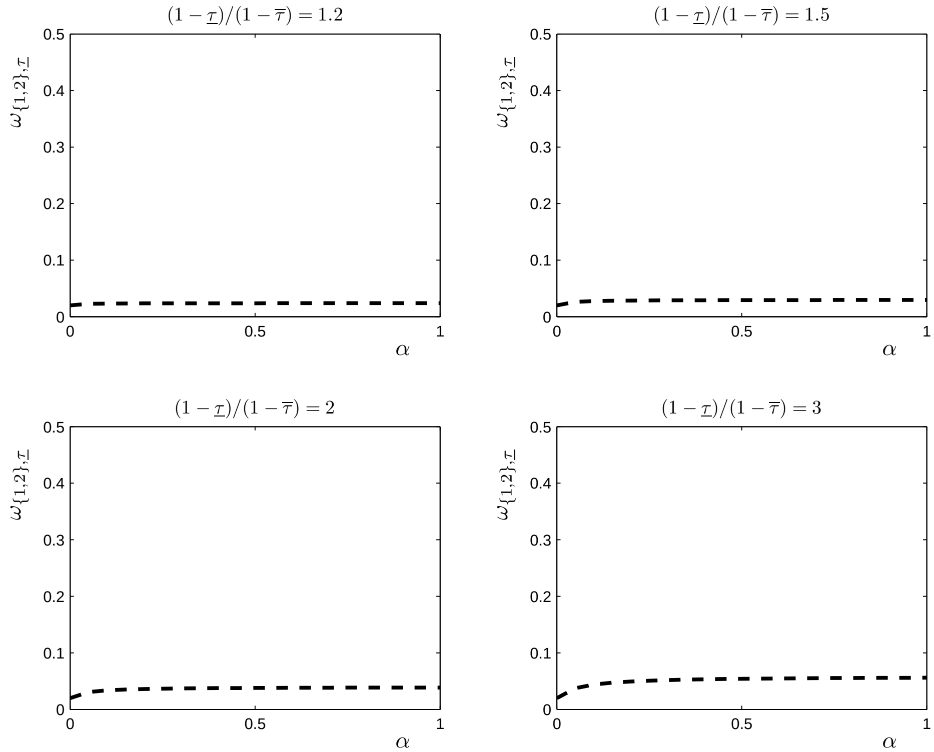

Figure 9: Effect of α on Optimal Extraction Rates under $\rho = 0$ and $\eta = 1.01$

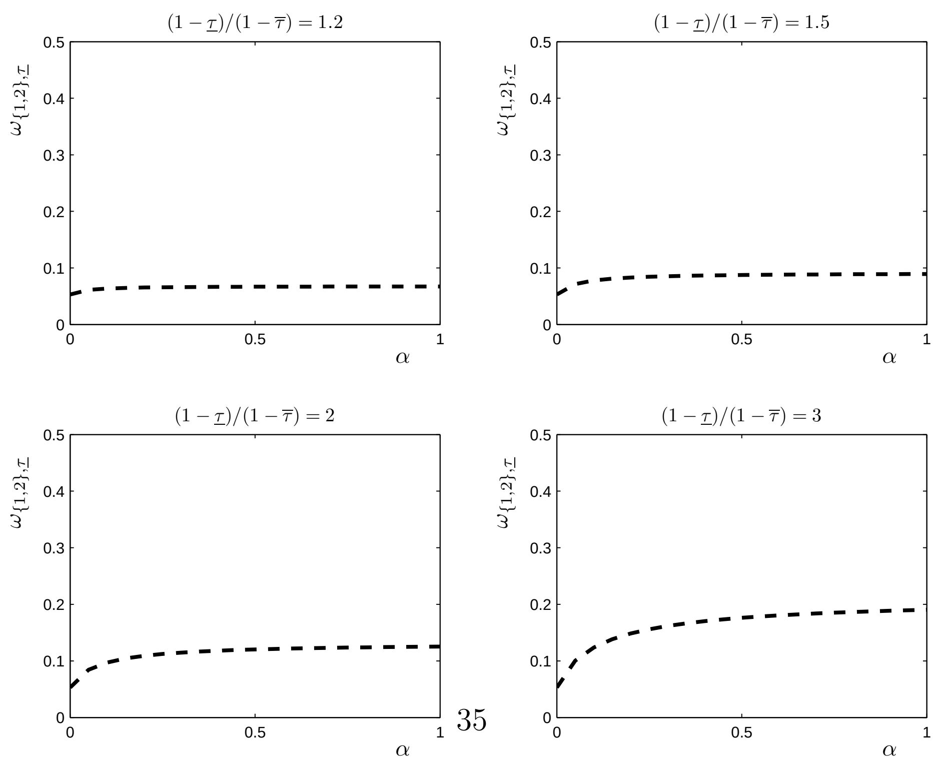

Figure 10: Effect of α on Optimal Extraction Rates under $\rho = 0$ and $\eta = 1.5$

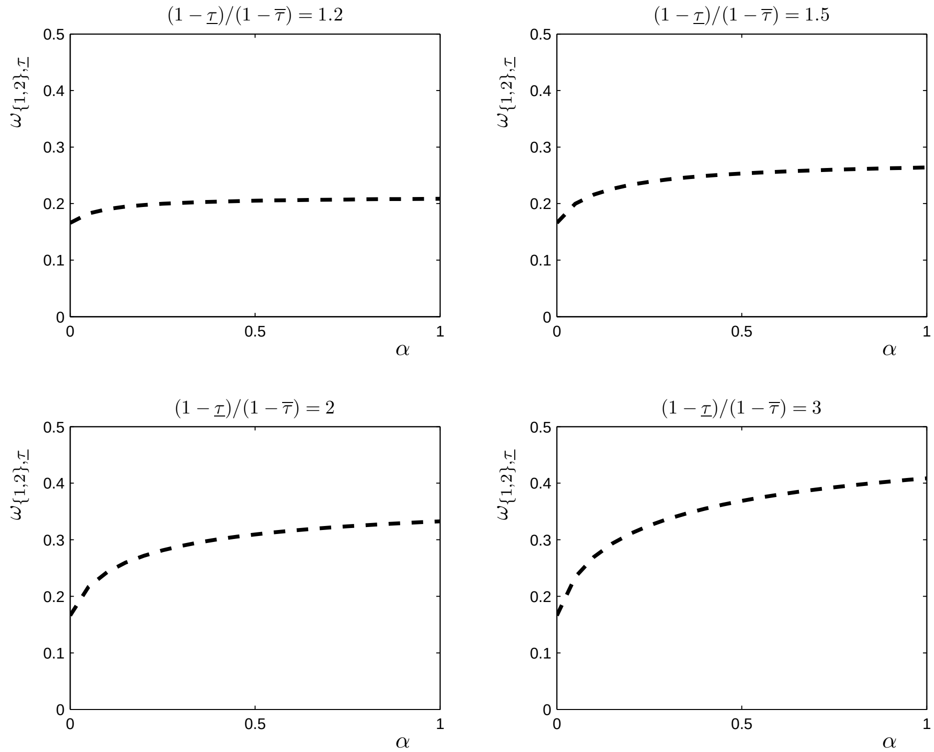

Figure 11: Effect of α on Optimal Extraction Rates under $\rho = 0$ and $\eta = 2$

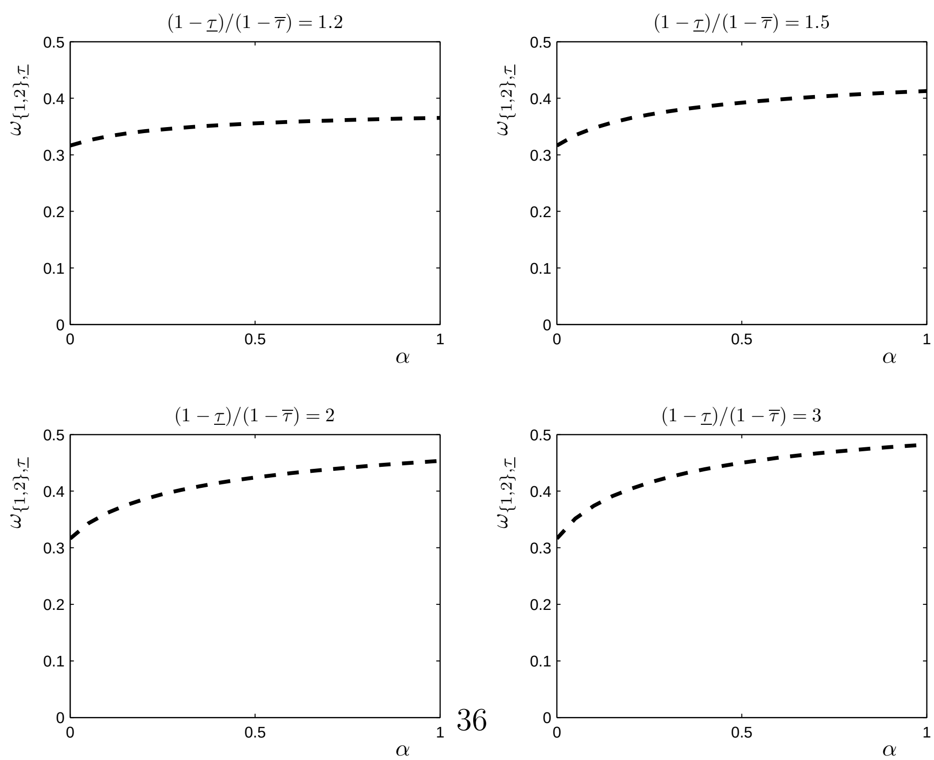

Figure 12: Effect of α on Optimal Extraction Rates under $\rho = 0$ and $\eta = 2.5$

References

H. Bohn and R. T Deacon. Ownership Risk, Investment, and the Use of Natural Resources. *Amer. Econ. Rev.*, 90(3):526–549, 2000.

P. Dasgupta and J. Stiglitz. Market Structure and Resource Extraction under Uncertainty. *Scand. J. Econ.*, 83(2):318–333, 1981.

Y.H. Farzin. The Effect of the Discount Rate on Depletion of Exhaustible Resources. *J. Pol. Econ.*, 92(5):841–851, 1984.

C. Hajzler. Resource-based FDI and Expropriation in Developing Economies. Mimeo, University of Western Ontario, 2008.

J. Hartwick and P.A. Sadorsky. Duopoly in Exhaustible Resource Exploration and Extraction. *Can. J. Econ.*, 23(2):276–293, 1990.

L. Hotte, N.V. Long, and H. Tian. International Trade with Endogenous Enforcement of Property Rights. *J. Dev. Econ*, 62(1):25–54, 2000.

H.G. Jacoby, Li G., and Rozelle S. Hazards of Expropriation: Tenure Insecurity and Investment in Rural China. *Amer. Econ. Rev.*, 92(5):1420–1447, 2002.

C.R. Kennedy. Multinational Corporations and Expropriation Risk. *Multinat. Bus. Rev.*, Spring, 1993.

S.J. Kobrin. Expropriation as an Attempt to Control Foreign Firms in LDCs: Trends from 1960 to 1979. *Int. Organ.*, 28(3):329–348, 1984.

C. Koulovatianos and L.J. Mirman. The Effects of Market Structure on Industry Growth: Rivalrous Non-Excludable Capital. *J. Econ. Theory*, 133(1):199–218, 2007.

P. Lasserre. Exhaustible Resource Extraction with Capital. In A. Scott, editor, *Progress in Natural Resource Economics*, pages 178–202. Clarendon Press, London, 1985.

D. Levhari and L.J. Mirman. The Great Fish War: An Example Using a Dynamic Cournot-Nash Solution. *Bell J. Econ.*, 11(1):322–334, 1980.

N. V. Long. Resource Extraction under the Uncertainty about Possible Nationalization. *J. Econ. Theory*, 10(1):42–53, 1975.

F. Monaldi. *The Political Economy of Oil Contract Renegotiation in Venezuela*. MIT press, 2008.

S. Salant. Exhaustible Resources and Industrial Structure: A Nash-Cournot Approach to the World Oil Market. *J. Pol. Eco.*, 84(5):1079–1093, 1976.

A. Tornell and P. Lane. The Voracity Effect. *Am. Econ. Rev.*, 89(1):22–46, 1999.

A. Tornell and A. Velasco. The Tragedy of the Commons and Economic Growth: Why Does Capital Flow from Poor to Rich Countries? *J. Pol. Econ.*, 100(6):1208–1231, 1992.

R. Van der Ploeg. Voracious Transformation of a Common Natural Resource into Productive Capital. *Int. Econ. Rev.*, 51(2):365–381, 2010.