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Optimal Completeness of Property Rights on Renewable Resources in Presence of Market Power*

Alexandre Croutzet†, *Pierre Lasserre*‡

Abstract

There are many instances where property rights are imperfectly defined, incomplete, or imperfectly enforced. The purpose of this normative paper is to address the following question: are there conditions under which partial property rights are economically efficient in a renewable resource economy? To address this question, we treat the level of completeness of property rights as a continuous variable in a renewable resource economy. By design, property rights restrict access to the resource, so that they may allow a limited number of firms to exercise market power. We show that there exists a level of property rights completeness that leads to first-best resource exploitation; this level is different from either absent or complete property rights. Complete rights are neither necessary nor sufficient for efficiency in presence of market power. We derive an analytic expression for the optimal level of property rights completeness and discuss its policy relevance and information requirements. The optimal level depends on i) the number of firms; ii) the elasticity of input productivity and iii) the price elasticity of market demand. We also find that a greater difference between the respective values of input and output requires stronger property rights. In fact, high profits both imply a severe potential commons problem and may be the expression of market power; strong property rights limit the commons problem; their incompleteness offsets market power. Biology also impacts the optimal quality of property rights: when the stock of resource is more sensitive to harvesting efforts, optimal property rights need to be more complete.

Keywords: Institutions; property rights; entry; market power oligopoly; common access.

Codes JEL/JEL Codes: K, L1, Q2, Q3.

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† Université du Québec à Montréal. Email: croutzet.alexandre@uqam.ca.

‡ Université du Québec à Montréal; CIREQ, and CIRANO. Email: lasserrepierre007@gmail.com.

1 Introduction

Among various institutions, property rights are perhaps the most fundamental as they act both as an incentive for the creation of other institutions (in order to define and protect them - North (1990)) and as a key explanatory component of social and economic behaviors. In fact, as highlighted by Libecap (1989), property rights critically affect decision making regarding resource use and hence affect economic behavior and performance. Moreover, by allocating decision making authority, property rights also determine who are the economic actors in a system and define the distribution of wealth in a society.

This paper questions the notion that property rights need to be complete in order to be perfect and that the sole socially justifiable reason for incomplete rights has to do with the costs associated with their definition or their enforcement. Are there instances where, absent such costs, partial property rights are economically efficient? For concreteness, we analyze the desirability of incomplete property rights for a renewable resource. Indeed, renewable resources arguably provide the richest set of existing theoretical analyses on the subject as well as they provide countless examples of situations where property rights are neither perfectly defined nor completely enforced. As a rule, such situations are considered suboptimal.[2]

The basic idea at the root of the paper is not new and applies to virtually any economic activity. It is that market power keeps production below the socially desirable level while the lack of property rights on an input leads to its overexploitation (see Hotte et al., 2013). Clearly the coexistence of both so called market failures may be socially preferable to the presence of each separately; it has been shown that the "right" degree of market power can "cure" the tragedy of the commons and lead to a Pareto optimum (Cornes et al., 1986), an intuition already present in Hotelling (1931). Nonetheless, incompleteness in property rights is overwhelmingly considered an imperfection, although

[2] As Costello et al. (2015) remark, 'we rarely observe [property rights and other economic instruments] being implemented in their pure form as economic models would suggest. Instead, we tend to observe hybrids where only part of the resource is subsumed within a market structure.'

sometimes this imperfection is given sensible justifications such as enforcement costs[3] or the very nature of the goods involved, public goods for example.

This paper questions the absolute desirability of complete property rights. In a world where some degree of market power is the rule rather than the exception, complete property rights should perhaps also be the exception. Economic agents who set prices rather than taking them as given, including when this is done indirectly by lobbying or other forms or rent seeking, should probably not enjoy complete exclusive rights on the products concerned or the inputs used to produce them.

We show that complete rights are neither necessary nor sufficient for efficiency in a resource industry where a limited number of firms compete with each other. Partial property rights are found to be efficient in presence of market power: The lower the number of firms is, the weaker property rights should be. Although the analysis is purely normative, it suggests that numerous instances of imperfectly enforced or incomplete property rights are not necessarily signs of imperfect institutions; they may be compatible with an adequate adjustment of the quality of property rights. The paper defines the level of property rights incompleteness as a measurable parameter; provides examples of instances where this definition applies; and gives an accurate formula defining the level of property rights completeness that should be aimed at as function of observable variables. Besides identifying empirical circumstances under which the model applies, the paper refers to several researches that have discussed or investigated similar situations.

Renewable resources have exhibited increasing scarcity together with imperfect exclusion (Stavins, 2011), highlighting the necessity that the resource be protected by property rights or by other means. Just as importantly, a renewable resource cannot be produced by industrial methods and its location is defined by nature. This tends to limit the number of actors involved in its exploitation while, on the other hand, free access tends to swell it. The effect of property rights and their degree of completeness

[3] In presence of definition or enforcement costs, the first-order condition for optimality requires the equality of marginal costs and marginal benefits of definition or enforcement. This equality normally occurs at lower marginal cost levels than required for complete definition or enforcement (Nostbakken, 2008).

will depend on the number of actors as well as it may affect it.

Empirically, market power was a feature of some fisheries before fish stocks became a preoccupation. In earlier times, "the fish stocks were so large and robust that expanded fishing hardly affected the catches. That is why the occasional “fish war” was not for possession of dwindling fish stocks - they were not dwindling. The fish wars were fought to capture, for one country’s vessels, both monopoly positions over the richest markets and possession of places for vessels to winter or to dry fish." (Scott, 2000). Increasing biomass scarcity and the subsequent introduction of property rights could not be expected to reduce market power; rather the concern was that they might promote it. As a matter of fact, "By far the most serious initial policy problem [in introducing ITQ’s] was the transition: who should get quotas, how large should they be,...?" (Arnasson, 2000). The question of market power "was raised at every public hearing the Mid-Atlantic Fishery Management Council held for the ITQ program in the surf clam and ocean quahog fishery and at meetings of other councils as they considered ITQ management." (Anderson, 1990). "An important effect of ITQ regimes where the initial allocation of the ITQ goes to vessel owners is to change, or threaten to change, the distribution of bargaining power between buyers and sellers of marine products" (Anderson, 2000).

Market power combines with property rights to affect economic behavior; although its importance may vary empirically, it may be or it may become an important factor in many renewable resource industries as further witnessed by the substantial literature that we review in the next section. We assume that some degree of market power may be present in the industry and we investigate what level of completeness of property rights is then desirable from a normative point of view. The way we define it, the degree of completeness of a property right is measurable. We show that the first best optimum can be achieved if and only if this degree of completeness satisfies a simple formula reflecting the potential inefficiency resulting from market power as measured by the Lerner index and by the number of firms, and the potential inefficiency from unlimited common pool access as measured by the elasticity of production to harvesting effort. As a result, our normative analysis may be used as a step toward the design of efficient incomplete property rights regimes. To anticipate on some results, the more price inelastic market demand, the higher the elasticity of production to fishing effort, and the lower the number of firms in the fishing industry, the weaker property rights on the biomass should be.

The remainder of the paper is organized as follows. In the next section, we examine the literature. Section 3 presents the biological and technological features of the model while Section 4 characterizes its efficient steady state equilibrium. Property rights (Subsection 4.1) are modelled in such a way that their level of completeness is expressed by a single parameter that varies between zero and unity, and is measurable. Firms adopt a Cournot-Nash behavior; they determine their own harvesting effort while considering the level of completeness of property rights and their assignment to firms as given, and taking other firms harvest decisions as given. Having characterized the resulting steady state equilibrium in Subsection 4.2, we turn in Section 5 to the main results of the paper. We first establish the existence of a level of property rights completeness leading to first best resource exploitation. Then, in Subsection 5.1 we find an explicit formula for that optimal completeness level. In Subsections 5.2 and 5.3, we discuss policy relevance and dynamic issues, and, in Subsection 5.4, we explain how the optimal completeness level depends on tastes, biology, technology, and the number of firms. Section 6 recapitulates and concludes.

2 Relation to the literature

An early economic literature examines the effects of market power on the exploitation of renewable resource (Scott, 1955, is a classical reference) or on the exploitation of non renewable resources (Salant, 1976; Loury, 1986) in presence of complete private property rights.

There is also an extensive literature on situations where property is common or outright absent. This includes papers related to the tragedy of the commons, where the number of actors and the fact that they do not cooperate[4] are at the root of the problem caused by the absence of private property rights (e.g., Gordon, 1954; and Hardin, 1968), as well as papers on the non cooperative exploitation of a renewable resource in common access when individual producers wield market power (e.g., Levhari and Mirman, 1980; Datta and Mirman, 1999; Karp,1992; Pintassilgo et al., 2010). In these papers, the focus is on the game theoretic outcome. Similar analyses have also been carried out on the competitive exploitation of a non renewable resource in common access (e.g., Dasgupta and Heal, 1979).

More closely related to our paper is a literature looking for the optimal number of non cooperative firms exploiting a renewable resource in common access (see Cornes *et al.*, 1986 for a study in a static context; and Mason and Polasky, 1997 for a dynamic context). Instead of looking for the optimum number of firms under conditions of free access, we treat property rights as partial and look for their optimal level of incompleteness given the number of firms. The complete absence of property rights is only one possibility. In fact our paper shares some common ground with Heintzelman *et al.* (2009) who show that there exists a specific organization of the fishing industry, partnerships, that can be socially optimal in a common pool resource. In this paper, we consider an oligopolistic market structure and show that a first-best social optimum can be achieved when the resource is partially protected. We show that the socially optimal quality of property rights is a function of technology, biology, preferences, and the number of firms.

Partial property rights have been considered before: Bohn and Deacon (2000) empirically study the effect of insecure ownership on ordinary investment and natural resource use. They treat the degree of property-rights completeness as exogenous and do not question the desirability of completely secure rights. Several papers involving trade and natural resources treat the completeness of property rights as endogenous (Hotte *et al.*, 2000; Copeland and Taylor, 2009; Tajibaeva, 2012); they do so without questioning the desirability of completeness. Hotte *et al.* (2000) consider a small, price taking, economy in which trade can lead to more complete property rights and a higher level of resource

[4] When agents cooperate, common pool resources can be optimally exploited (Ostrom, 1990).

stock at the steady state but may result in welfare loss due to the existence of enforcement costs. Tajibaeva (2012) also emphasizes the importance of enforcement costs. In Copeland and Taylor (2009), property rights are incomplete because of monitoring problems; complete protection of the resource would be efficient but is not feasible. Our paper shows that, even if the complete protection of the resource were feasible and absent any enforcement costs, complete protection would be inefficient in presence of market power.

Engel and Fisher (2008) are also concerned with efficiency. However, they do not consider a decentralized economy. They study how a government should contract with private firms individually to exploit a natural resource. Property rights do play a role, as there is a possibility for the government to optimally expropriate firms. Engel and Fisher consider the impact of expropriation in presence of uncertainty, market power and an irreversible fixed cost. Costello and Kaffine (2008) adopt a similar contractual approach. They study the dynamic harvest incentives faced by a renewable resource harvester with insecure property rights. A resource concession is granted for a fixed duration after which it is renewed with a known probability if a target stock has been achieved. They show that complete property rights are sufficient for economically efficient harvest but are not necessary. They further show that some minimum length of tenure is required to induce the efficient path; this minimum length is a decreasing function of the renewal probability and the growth rate. They conclude by saying: "Next steps in this vein could include combining the appropriator's incentives with the regulator's objective to design efficient incomplete property rights regimes." Our simple model goes in that direction. Beyond major differences in formulation and approach, it differs from Costello and Kaffine (2008) and Engel and Fisher (2008) in that the level of completeness of property rights is the endogenous variable under study. Complete rights are neither necessary, nor sufficient for efficiency: complete rights are inefficient in our model.[5]

The resource problem considered in this paper is a second best problem (Lipsey and Lancaster, 1956). In an economy where the number of firm is finite and firms exercise

[5] Grainger and Costello (2011) provide an empirical investigation of the impact of insecure property rights on the value of fishing quotas in Canada, New Zealand and the US. They illustrate the fact that different fishing ITQ regimes translate into different strengths of property rights.

market power, property rights are established by a social planner that does not otherwise control firms. It is shown that the first best can be achieved by partial property rights provided some conditions on technology and preferences are satisfied.

3 The model

3.1 Resource, producers, technologies and consumers

Consider n firms or fishermen $i = 1, ..., n$ having access to a homogeneous stock S of renewable resource. Our analysis will focus on steady states of the bioeconomic model. However it is useful to go over its dynamics before doing so to emphasize the combination of biological, technological, and institutional characteristics that determine these steady states under various property right levels of completeness.

The change $\dot{S}$ of the stock depends on total harvest H and, through a continuously differentiable natural growth function $G(S)$ (See Hanley et al., 1997 and, for more complex forms, Clark, 1990), on stock size:

$$\dot{S} = G(S) - H \tag{1}$$

A steady state equilibrium is defined by the condition $\dot{S} = 0$, implying:

$$G(S) = H \tag{2}$$

Harvesting by firm i, $h_i(e_i, S)$, depends on its own effort e_i, whose unit cost w is fixed and exogenous, and on the stock of resource. Both efforts and resource stock are essential to harvesting - $h_i(0, S) = 0 \ \forall S$ and $h_i(e_i, 0) = 0 \ \forall e_i$ - and we have $\frac{\partial h_i(e_i,S)}{\partial e_i} > 0$ when $S > 0$, $\frac{\partial h_i(e_i,S)}{\partial S} > 0$ when $e_i > 0$, and $\frac{\partial^2 h_i(e_i,S)}{\partial e_i \partial S} > 0$ when e_i or $S > 0$.[6]

Total harvest is the sum of individual harvests: $H = \sum_{i=1}^{n} h_i(e_i, S)$. As total harvest is a function of individual efforts and the biomass, equation (2) defines the equilibrium biomass as implicit function of the vector $V = (e_1, ..., e_n)$ of individual efforts:

$$S = \widetilde{S}(V) \tag{3}$$

[6] Note that this harvesting function is not necessarily quasiconcave. It includes widely used functions such as $h(e_i, S) = Ae_iS$ which exhibits positive returns to scale to effort and the biomass or the Voltera function studied by Neher (1974).

Expression (2) is the traditional bioeconomic equilibrium equation found in the literature. It defines steady state equilibria compatible with harvest levels H induced by effort levels V. Given any biomass level, total harvest increases with individual effort. However higher efforts reduce the equilibrium biomass so that, as is well known, diminishing marginal productivity of individual effort is neither necessary nor sufficient for the existence of a stable steady state equilibrium.[7]

We further assume that all firms share the same harvesting technology with constant returns to effort given the resource stock level. The assumption of a unique technology allows the analysis to skip the important but theoretically well understood step whereby inefficient firms are weeded out of the industry, allowing only the survival of firms using the efficient technology. Indeed such an outcome is arguably an advantage of systems involving transferable property rights of the kind examined below; the contribution of this paper is elsewhere, in the analysis of the incentives required for such technologically efficient firms to behave optimally. Industry efficiency does not require the assumption of constant returns, however. We use it to avoid the complication of studying optimum firm size and its implication on the number of firms at the various equilibria that arise depending on property rights. Under that assumption, any given total effort has the same cost whatever the number of firms and whatever the repartition of individual efforts, as shown now.

Identical technologies with constant returns to effort imply that $h_i(e_i, S) = h(e_i, S)$ and $\frac{\partial^2 h(e_i,S)}{\partial e_i^2} = 0 \ \forall \ i, \ S$. Constant returns to efforts also imply that:

$$h(e_i, S) = e_i f(S) \tag{4}$$

so that:

$$H = Ef(S) \text{ with } E = \sum_{i=1}^{n} e_i \text{ and } f(S) = h(1, S) \tag{5}$$

[7] The steady state supply is also unusual; it may decrease rather than increase as a function of a firm's effort. Let $\frac{dh_i(e_i,S(V))}{de_i} \equiv \frac{\partial h_i(e_i,S(V))}{\partial e_i} + \frac{\partial h_i(e_i,S(V))}{\partial S}\frac{\partial S}{\partial e_i}$ denote the equilibrium marginal productivity of individual effort by Firm i. If it exists, the equilibrium level of biomass is lower, the higher the fishing effort: $\frac{\partial S}{\partial e_i} < 0$. Consequently a sufficient condition for $\frac{dh_i(e_i,S(V))}{de_i} > 0$ is the equilibrium biomass $S(V)$ to exceed the Maximum Sustained Yield level MSY as $\frac{\partial h_i(e_i,S(V))}{\partial S} < 0 \ \forall \ S > MSY$.

Given the biomass, total harvest only depends on total effort. As a result, the steady state biomass only depends on total effort.[8] We define the steady state harvest and biomass corresponding to that special case of (3) with identical constant returns technologies as

$$H\left(E\right)=Ef(S\left(E\right))\text{ and }S(E)\equiv\widetilde{S}(V) \tag{6}$$

Equation (2) is not sufficient to uniquely determine H and S. Consumer preferences, represented by an aggregate inverse demand function $P(H)$, determine which of the pairs (H,S) verifying this equation is economically efficient. In the next section, we define the economically efficient steady state, which under our standard assumptions, is unique.

3.2 The social optimum

Let the net consumer surplus be $C(H)=U(H)-P(H)H$ where $U(H)=\int_0^H P(u)du$. Let the net producer surplus be $\sum_{i=1}^{n}\left(P(H)h(e_i,S)-e_iw\right)$. With identical constant return technologies, this equals $\left(P(H)f(S)-w\right)E$. The instantaneous social welfare function is thus $W(H,E)=U(H)-wE$ with $U'\left(H\right)=P\left(H\right)$. The first-best problem is to maximize cumulative social welfare by choice of individual efforts. We will confine the analysis to the steady state so that efforts and the biomass are constant. However, it is useful to use a dynamic formulation of the planner's problem. As is well known, this highlights the dynamic dimension of the user cost of the resource, allowing it to be distinguished from its counterpart arising from a static congestion problem. Thus the planner's problem is:

$$\max_{e_1,\dots,e_n}\int_0^{\infty}e^{-rt}\left(U\left(H\right)-wE\right)dt$$

subject to (5) and (1) where r is the discount rate.

The current value Hamiltonian may be written as

$$\mathcal{H}\left(S,E,\mu\right)=U\left(Ef(S)\right)-wE+\mu\left(G\left(S\right)-Ef(S)\right)$$

[8] This assumption is explicitly or implicitly made in most fishery papers and textbooks. For an alternative treatment involving firms with different technologies, see Arnason (1990).

where μ is the current value costate variable associated with S, the shadow price of the resource input. The first-order condition for effort at an interior optimum is:

$$(P(H) - \mu) f(S) - w = 0 \tag{7}$$

The maximum principle also implies:

$$\dot{\mu} = -(P(H) - \mu) E f'(S) + \mu (r - G'(S))$$

In steady state equilibrium $\dot{\mu} = 0$ and (2) as well as (6) hold so that:

$$\mu = P(H) \frac{E f'(S)}{r - G'(S) + E f'(S)} \tag{8}$$

Substituting into (7) implies that the steady state Pareto optimal total effort is such that:

$$P(H) \left[1 - \frac{E f'(S)}{r - G'(S) + E f'(S)}\right] f(S) = w \tag{9}$$

where H and S are functions of E given by (6).[9] This condition says that the value of the increase in harvest provided by one extra unit of collective effort, $P(H) f(S)$, net of its negative impact on the biomass $\mu f(S)$, must equal the unit cost of effort w. It is evaluated at the steady state equilibrium where μ is given by (8).

Assuming that the second order condition is satisfied,[10] (9) defines the optimal total level of effort $E^* = \sum_{i=1}^{n} e_i^*(n)$ as independent of n. The Pareto optimum equilibrium resource stock and harvest depend on E^* only:

$$S^* = S(E^*) \ \ \forall n; \ H^* = E^* f(S(E^*)) \ \ \forall n \tag{10}$$

Although the total effort level is determined, its repartition across firms is undetermined.[11] One particular solution is $e_1^*(n) = e_2^*(n) = ... = e_n^*(n) = e^*(n)$ with $e^*(n) = \frac{E^*}{n}$.

[9] The static version of this expression characterizing the tragedy of the commons (sometimes assimilated to a congestion model) can be obtained by noting that $S' = \frac{f}{G' - Ef'}$ so that, if $r = 0$, $P(H)[f(S) + ES' f'(S)] = w$.

[10] Differentiating the left hand side of (9) with respect to E, the second order condition is

$$P(H)[(f'(S(E)) + 1) S'(E) + S''(E) E] \leq 0$$

Since $f' > 0$ and $S < 0$, this condition is satisfied if and only if the term $S''(E) E$, which may be non negative, is not sufficient to offset the first term in the expression between brackets.

[11] See G. Stevenson (2005) p. 38 on the classic indeterminacy of individual efforts in presence of constant returns to scale at the firm's level.

Whether or not this particular solution holds, the pair (H^*, S^*) defines the socially optimal steady-state with $H^* = G(S(E^*))$.

4 Property rights and the decentralized economy

4.1 Property rights

According to Scott (2000),[12] the characteristics of a property right are exclusivity, duration, security (or quality of title), and transferability; a property right is said to be complete if it has all these four characteristics, each one to the fullest possible extent.[13] This paper focuses on exclusivity, assuming that all other three characteristics are present to the fullest extent if a right is present at all. Exclusivity will be present at various degrees of completeness.

In order completeness to be possible, whether with respect to exclusivity or to any of the other three property right characteristics, the object to which the right pertains must be well defined. Consider an ITQ on some fish resource. If the ITQ covers a specific zone which is smaller than the habitat of the fish resource, as, e.g. in Costello et al. (2015), then the right on the resource is only partially defined because fish migrates between protected and unprotected zones; it confers exclusive use only on part of the object. This can be analyzed as incompleteness. Alternatively, consider an ITQ covering the complete relevant zone. The right is well defined in that respect. However if the right is not completely enforced, with some false reporting or poaching going on, it does not provide complete exclusivity to its owner. The analysis is similar to the case of imperfect definition.

In production contexts, property rights usually protect both outputs and inputs.

[12] For a wider view, see Ostrom (2010).

[13] Scott considers that a property right in land or water confers his owner : '(a) power to use the thing (or manage it); (b) power to dispose of it (to sell it or grant it); and (c) power to take its yield (e.g. as a crop, rent or royalty)'.

To Schlager and Ostrom (1992), a right and the power it confers are the same thing: 'In regard to common-pool resources, the most relevant operational-level property rights are "access" and "withdrawal" rights. These are defined as:

Access: The right to enter a defined physical property.

Withdrawal: The right to obtain the "products" of a resource (e.g., catch fish, appropriate water, etc.).'

They provide output appropriation - the owner gets the benefit from her production; they provide input exclusion - an input is used exclusively by or for the benefit of its owner. Hotte *et al.* (2013) consider issues of input exclusion and output appropriation simultaneously. They show that property rights on inputs versus property rights on outputs have opposite effects on input use and on output. Weak property rights on a natural resource input limit exclusion and encourage harvest while weak property rights on output discourage harvest. Indeed, the distinction between input and output rights, whenever possible, appears of primary importance. However, in most regulatory regimes, exclusion rights (on the input) are enforced by controlling the output. For example, fishing quotas such as ITQ's are rights to land and sell fishes (i.e. outputs) that aim at controlling access to the resource input (fish in the water). As a result, the distinction between input exclusion and output appropriation may be blurred.

The tragedy of the commons is a problem of input exclusion: the biomass that combines with other production inputs (such as boats and nets in the case of the fishery) to produce a catch cannot be used while excluding other users. Suppose that some property right addresses that problem, an ITQ for example. If the right is complete, then access to the resource input is completely exclusive despite the fact that the ITQ is defined on the output. There is a one to one correspondence between the number of fishes imputed to the quota and the resource input used, which takes the form of fishes taken out of the water.

If the right is incomplete, the number of fishes taken out of the water is higher than the total number of fishes allowed under the ITQ system. This disconnection between input used on one hand, and declared or recorded output on the other hand, happens for various reasons and may take various forms. It may be fraudulent if the ITQ holder sells part of her catch on a secondary market or if she wrongly records part of the catch as originating from areas that are not covered by the quota system; indeed controls on ITQ's holders may be insufficient. Furthermore fishing of the controlled species by fishermen outside the quota system may be going on, whether outright illegal, tolerated, or perfectly legal. In Costello et al. (2015), fishing rights are defined on a share of the resource, the rest being in open access. Dupont and Grafton (2001) provide an illustration of such systems in Nova Scotia. The authors describe a rights-based fishery management system in which ITQ on a share of a total allowable catch ("TAC") coexist with a non-ITQ competitive fishing pool on the remaining share of the TAC.

Hannesson (2004) and Stavins (2011) provide other illustrations mentioning fish species that migrate between exclusive economic zones - 200 miles from coastlines - generally subject to well established rights based management systems, and open ocean - beyond the 200 miles limit - where that stock is in open access. Grainger and Costello (2011) give examples of fishing ITQ regimes in New Zealand where property rights are insecure either because the species are migrating beyond territorial waters or because of significant illegal harvesting.[14] Another interpretation of incomplete rights arises if firms harvest a renewable resource in an uncertain institutional context where the resource may turn out to be perfectly protected or in open access. In all such situations, the fishery combines features of perfect exclusion with features of free access to the resource input.

We will model the full range of possibilities between complete property rights insuring exclusive control of the input, and free access to the input. We will do so while assuming that private or public costs of enforcement and definition are nul. This assumption is made to avoid obscuring the analysis with elements that are already known and outside the purpose of the paper, which is to highlight a normative reason for incomplete property rights and characterize its policy implications.

Let θ denote an indicator of the level of completeness of property rights on the resource with $\theta \in [0, 1]$. Property rights are defined on a proportion $(1 - \theta)$ of the total harvest while a proportion θ is in common access. Each firm is attributed a share β_i of the protected harvest, so that $\sum_{i=1}^{n} \beta_i = (1 - \theta)$. The polar cases $\theta = 0$ and $\theta = 1$ respectively corresponds to a situation where property rights are complete and absent.

[14]The South Pars/North Dome gas field provides a non-renewable resource illustration of a combination of well-defined property rights and open access. The South Pars/North Dome gas field is the world's largest conventional gas field; it spans Iranian and Qatari territorial waters. Although each country has its own reserve, the field is in common-access and encroachments are frequent.

It will be convenient to think in terms of ITQ's. When $\theta = 0$, so that $\sum_{i=1}^{n} \beta_i = 1$, the sum of all attributed and perfectly enforced quotas is equal to the total amount of resource harvested. When $\theta = 1$, no quotas are attributed, $\sum_{i=1}^{n} \beta_i = 0$, and the total amount of resource harvested is in common access. Interior values of θ mean that perfectly enforced property rights are defined on a proportion $(1 - \theta)$ of the harvest, leaving a proportion θ in open access. In steady state, the total resource in open access is then $\theta G(S)$.

This parsimonious representation of incomplete property right models the situations evoked above fairly well. For example if ITQ's are issued to fishing firms for catches made in specific areas while the total fish stock inhabits a wider area, $1 - \theta$ represents the proportion of the total habitat protected by ITQ's while θ is the proportion under common access. The firms complement their quotas by harvesting in the common access zone.[15] If the problem is not the geographic definition of the protection but incomplete enforcement, then the total catch is $G(S)$ in steady state, of which $(1 - \theta) G(S)$ is effectively allocated in the form of ITQ's while a quantity $\theta G(S)$ sneaks out of the enforcement or the reporting system. This unaccounted harvest is accessible to the same firms that hold quotas. If they do not harvest more than they report, they know that others will do and they will not benefit from their restraint. So this part of their objective function is modelled as common access as described now.

The firms compete for the part of the resource which is in common access. As in Gordon (1954) and subsequent literature, we assume that the share of the common access portion that each firm appropriates is an increasing function $\Psi^i(e_i, \sum_{j \neq i}^{n} e_j)$ of its own harvesting efforts and a decreasing function of the combined harvesting efforts from others. With identical constant returns technologies it is also natural to assume that fishermen get the same share and face the same marginal productivity of effort if they all make the same effort; in other words, $\Psi^i(e_i, \sum_{j \neq i}^{n} e_j) = \Psi(e_i, \sum_{j \neq i}^{n} e_j)$. Following much of the literature, we make the following assumption for Ψ.

[15] The formulation also applies (with $n = 1$) if the protection is attributed to some single owner, as in Costello et al. (2015) while the unprotected zone is open to some other set of firms. The firms' objectives and resulting harvest decisions presented further below have to be modified accordingly.

Assumption 1 *The harvest share function* $\Psi(e_i, \sum_{j\neq i}^n e_j)$.

1. $\Psi(e_i, \sum_{j\neq i}^n e_j)$ *is twice continuously differentiable;*

2. $\Psi(0, \sum_{j\neq i}^n e_j) = 0$ *and* $\Psi(e, 0) = 1$*;* $\sum_{i=1}^n \Psi(e_i, \sum_{j\neq i}^n e_j) = 1$*;*

3. $\Psi(\lambda e_i, \sum_{j\neq i}^n \lambda e_j) = \Psi(e_i, \sum_{j\neq i}^n e_j)$*;*

4. $\Psi_1(e_i, \sum_{j\neq i}^n e_j) \geq 0$*, where the inequality is strict if* $\sum_{j\neq i}^n e_j > 0$*;* $\Psi_2(e_i, \sum_{j\neq i}^n e_j) \leq 0$*, where the inequality is strict if* $e_i > 0$*;*

5. $\Psi_{11}(e_i, \sum_{j\neq i}^n e_j) < 0$ *when* $e_i > 0$ *and* $\sum_{j\neq i}^n e_j > 0$*;*

Property #3 expresses the requirement that the shares be insensitive to the units of effort measurement. Property #2 is an accounting condition; Property #4 is the basic ingredient of the tragedy of the commons; Property #5 ensures that one fisherman cannot eliminate all others.

The harvest of firm i is the sum of its private quota and the portion of the common access harvest that it appropriates:

$$h(e_i, S) = \beta_i H + \Psi(e_i, \sum_{j\neq i}^n e_j)\theta H \tag{11}$$

where $H = Ef(S)$. Summing across n, and recalling that $\sum_{i=1}^n \beta_i = (1-\theta)$ and $\sum_{i=1}^n \Psi(e_i, \sum_{j\neq i}^n e_j) = 1$, shows that the aggregate condition $H = \sum_{i=1}^n h(e_i, S)$ is verified.

For the polar case of common access (i.e., $\theta = 1$, implying $\beta_i = 0$), firm i's harvest equals $\Psi(e_i, \sum_{j\neq i}^n e_j)G(S)$. For the polar case of complete rights protection (i.e., $\theta = 0$), firm i's harvest is $\beta_i G(S)$, its individual quota.

4.2 The firms' harvest decision

Each firm determines its harvesting effort considering as given the harvesting efforts of other firms, as well as the number of firms and the completeness of property rights. Firm i's problem is:

$$\max_{e_i(t)} \Pi_i = \int_0^\infty e^{-rt} \left(P(H)h(e_i, S) - we_i \right) dt \tag{12}$$

subject to (5), (1), and (11). The current value Hamiltonian is, using (11):

$$\mathcal{H}^i\left(S,e_i,m_i;E_j\right)=P(H)H\left[\beta_i+\Psi(e_i,\sum_{j\neq i}^{n}e_j)\theta\right]-we_i+m_i\left(G\left(S\right)-H\right)$$

where m_i is the current value costate variable associated with S for Firm i.

Using the fact that, by (5), $dH=f\left(S\right)de_i$ when $de_j=0\ \forall\ j\neq i$, the first-order condition for effort by Firm i at an interior optimum in Nash equilibrium is:

$$f\left(S\right)\left\{\left[\beta_i+\Psi(e_i,\sum_{j\neq i}^{n}e_j)\theta\right]\left[P'(H)H+P(H)\right]+\Psi_{e_i}(e_i,\sum_{j\neq i}^{n}e_j)\theta EP(H)-m_i\right\}=w \tag{13}$$

This condition expresses the equality of marginal revenue (net of the marginal biomass cost $m_if\left(S\right)$) with marginal cost of effort w. It is most easily understood if one considers the particular case of monopoly exploitation. Then $\beta_i=1$ and, since no other firms have access to the resource, $\theta=0$. The formula reduces to $f\left(S\right)\left\{\left[P'(H)H+P(H)\right]-m_i\right\}=w$. It differs from its counterpart that characterizes the social optimum, (7), in that the term $P'H+P$ replaces P: the monopoly equates marginal cost to marginal revenue rather than to price when it chooses output.[16]

The maximum principle also requires $\dot{m}_i-rm_i=-\frac{\partial\mathcal{H}^i}{\partial S}$ i.e.:

$$\dot{m}_i=m_i\left(r-G'\left(S\right)\right)-\left\{\left[\beta_i+\Psi(e_i,\sum_{j\neq i}^{n}e_j)\theta\right]\left[P'\left(H\right)H+P\left(H\right)\right]-m_i\right\}Ef'\left(S\right)$$

Setting $\dot{m}_i=0$ implies that the steady state value of m_i is:

$$m_i=\frac{\left[\beta_i+\Psi(e_i,\sum_{j\neq i}^{n}e_j)\theta\right]\left[P'\left(H\right)H+P\left(H\right)\right]Ef'\left(S\right)}{r-G'\left(S\right)+Ef'\left(S\right)} \tag{14}$$

Let $E_{-i}=\sum_{j\neq i}^{n}e_j$ and denote $\Gamma^i(e_i,E_{-i};\beta_i,\theta,n)$ the left-hand side of equation (13) with m_i given by (14), and where S and H are the functions of E given by (6); $\Gamma^i(e_i,E_{-i};\beta_i,\theta,n)$ is the marginal revenue per effort unit net of the biomass cost m_i as

[16] Condition (13) also differs from (7) in that the shadow price of the resource m_i chosen by a monopoly generaly differs from its social value μ. It can be shown that m_i is smaller than μ when i is a monopoly, but not sufficiently smaller to invert the standard result that a monopoly produces less than is socially optimal.

valued by Firm i in steady state Nash equilibrium. The n conditions $\Gamma^i(e_i, E_{-i}; \beta_i, \theta, n) = w$ together determine the steady state effort levels by each firm.

The solution of the system of equations ((13), (14) , (6)) depends on n, on θ, and on the combination of shares β_i.[17] Consider the symmetric solution when $\beta_i = \beta$; since $\sum_{j\neq i}^{n} \beta_j = 1 - \theta$, $\beta = \frac{1-\theta}{n}$ $\forall$ i. It follows from (14) that all firms hold the same unit valuation for the biomass $m_i = m$, so that the solution of each equation (13) is the same effort level. At the symmetric steady state Nash equilibrium, the level of input extended by each firm $\widehat{e}(\theta; n)$ is then implicitly defined by:

$$\Gamma(\widehat{e}, n, \theta) = w \;\forall\; \theta \in [0, 1] \tag{15}$$

where,$\forall$ i, $\Gamma(e, n, \theta) \equiv \Gamma^i(e, (n-1)\, e; \frac{1-\theta}{n}, \theta)$.

Equation (15) states that the marginal revenue Γ that the oligopolistic firm obtains by increasing its effort by one unit, net of what that firm loses in terms of the biomass that it is able to appropriate for itself, should equal the unit cost of effort w. The condition is affected both by the completeness of property rights measured by θ, and by the number of firms n which determines the amount of market power of each firm. Thus there is a possibility that completeness and market power combine in such a way that (15) imply the same effort level as condition (9) which characterizes Pareto optimality. This is what we show in the next section.

5 Efficient property rights

Before stating the main result, let us briefly return to the literature on market power and the tragedy of the common. In 1986, Cornes et al. considered a static model of the commons with n firms for the special case $\Psi(e_i, \sum_{j\neq i}^{n} e_j) = \frac{e_i}{e_i + \sum_{j\neq i}^{n} e_j}$. They showed that, in the absence of any private property rights but under conditions where access to the resource is limited to a specific group of n identical firms, there exists a number of firms that equates the equilibrium harvest under oligopoly with the Pareto optimal

[17] Assumptions on the inverse demand function ensuring the existence and the uniqueness of the Nash equilibrium are given in Gaudet and Salant (1991).

harvest. For the present model, we will refer to that number as $\bar{n}$ the "optimal number of firms in pure common access". It is defined by setting $\theta = 1$ in (15) and finding the level of n that ensures that (15), so restricted, coincides with the condition for Pareto optimality (9), thus ensuring that $\bar{n}\widehat{e}(1;\bar{n}) = E^*$.

When $\theta = 1$ and firms are identical, $\Psi = \frac{1}{n}$ and the steady state shadow value of the biomass given by (14) reduces to $m = \frac{1}{n}\frac{(P'H+P)nef'}{r-G'+nef'}$ so that $\Gamma(\widehat{e}, n, \theta) = \left\{[P'H+P]\frac{1}{n} - [P'H+P]\frac{1}{n}\frac{nef'}{r-G'+nef'} + yP\Psi_e ne\right\} f$. Thus $\Gamma(\widehat{e}, n, \theta)$ coincides with the left hand side of (9) (where $E = n\hat{e}$, $S = S(n\hat{e})$, and $H = n\hat{e}f(S(n\hat{e}))$) if the following condition is satisfied when $n = \bar{n}$:[18]

$$(P'H+P)\frac{1}{n}\left(1 - \frac{n\hat{e}f'}{r-G'+n\hat{e}f'}\right) + P\Psi_e n\hat{e} = P\left(1 - \frac{n\widehat{e}f'}{r-G'+n\widehat{e}f'}\right) \tag{16}$$

One notes that, for any level of e such that $ne = E^*$, the left hand side of (16) is lower than the right hand side when $n = 1$ since $\Psi_e = 0$ in that case and P' is negative. This expresses the fact that the marginal product value of effort, net of the private resource cost, is lower for the monopoly than it is for society. The opposite is true when $n \to \infty$ since the first term on the right hand side then vanishes while $\Psi_e ne$ must tend toward unity to express the fact - the tragedy of the commons - that each of the n firms then perceives the marginal product of its effort $\Psi_e e$ as accruing to itself solely.[19] As a result $\bar{n}$ exists.

Proposition 1 *When the number of oligopolistic firms is strictly above the optimal number $\bar{n}$ of firms in pure common-access, there exists a level of property rights completeness θ^* with $1 > \theta^* > 0$ such that the harvesting efforts chosen by the oligopolistic firms at the steady state Nash equilibrium sum up to the first-best industry level: $n\widehat{e}(\theta^*; n) = E^*$.*

Proof. Γ is a continuously differentiable function so that, applying the implicit function theorem to (15), the function $\widehat{e}(\theta; n)$ exists and is continuous.

[18] The result of Cornes et al. (1986) is obtained in a static model, which corresponds here to the special situation where r tends to infinity.

[19] If $\Psi(e_i, \sum_{j\neq i}^n e_j) = \frac{e_i}{e_i + \sum_{j\neq i}^n e_j}$ as in Cornes et al. (1986), then $ne\Psi_{e_i}(e, (n-1)e) = (n-1)/n$. We formally show in the proof of Proposition 2 that this result approximately holds for any function Ψ satisfying Assumption 1.

The Pareto-optimal number of firms $\bar{n}$ in pure common-access verifies the condition $\bar{n}\widehat{e}(1;\bar{n}) = E^*$. By (16) (and as shown by Cornes *et al.,* 1986) for all n higher than $\bar{n}$, individual efforts from the oligopolistic firms in the absence of property rights ($\theta = 1$) are higher than the optimal level: $\widehat{e}(1;n) > e^*(n), \forall n > \bar{n}$. Hence:

$$n\widehat{e}(1;n) > E^* \quad \forall n > \bar{n}$$

For all n higher than $\bar{n}$, in presence of complete property rights ($\theta = 0$), oligopolistic firms competing à la Cournot provide a lower than optimal level of effort:

$$n\widehat{e}(0;n) < E^* \quad \forall n > \bar{n}$$

As $\widehat{e}(\theta;n)$ is a continuous function of θ, the intermediate value theorem implies that, when $n > \bar{n}$, there exists a value of θ, $\theta^* \in]0,1[$ such that:

$$n\widehat{e}(\theta^*;n) = E^* \quad \forall n > \bar{n} \tag{17}$$

■

This result does not rely on the particular functional form of Γ as long as Γ is continuously differentiable in both e and θ.

Corollary 1 *When the number of oligopolistic firms is strictly above the Pareto optimal number of firms in pure common-access, complete property rights $\theta = 0$ and the absence of property rights $\theta = 1$ both lead to socially inefficient levels of harvesting efforts.*

Proof. The result follows from $n\widehat{e}(1;n) > E^*$ and $n\widehat{e}(0;n) < E^*$, $\forall n > \bar{n}$. ■

5.1 The social planner's problem

Consider a social planner who cannot specify agents' efforts directly but can choose the completeness of the property rights θ at no cost prior to their activities.[20] By Proposition

[20] In doing so, we do not imply that the quality of property rights is an handily available policy instrument to governments. The social planner is used as a conceptual tool to define the efficient quality of property rights. We do not address the question as to whether that quality is reached by society nor how. One may think that it may be reached by society through an evolution of negotiations and compromises, laws and regulations, public investments in the judiciary system and laws enforcement, etc.

1 the first-best is attainable, provided the number of firms in the industry exceeds $\bar{n}$, by setting $\theta = \theta^*$ as defined by (17) where E^* is defined by (9) and $\widehat{e}(\theta; n)$ is defined by (15).

The following proposition draws the implications of that analysis for any function $\Psi(e_i, \sum_{j \neq i}^n e_j)$ satisfying Assumption 1, in particular for the widely used particular case where $\Psi(e_i, \sum_{j \neq i}^n e_j) = \frac{e_i}{\sum_{i=1}^n e_i}$.

Proposition 2 *The optimal degree of completeness of property rights is approximately equal to:*

$$\theta^* \simeq \epsilon_c + \frac{1}{1 - n} \frac{\epsilon_c}{\epsilon_D}, \; n \geq \bar{n} \tag{18}$$

where ϵ_D is the price elasticity of market demand and ϵ_c is the long run net effort elasticity of harvest, both measured at H^* and E^*.

The approximation is exact if $\Psi(e_i, \sum_{j \neq i}^n e_j) = \frac{e_i}{\sum_{i=1}^n e_i}$. For other functions satisfying Assumption 1:

$$\frac{n+1}{n} \left[\epsilon_C + \frac{n}{n-1} \frac{\epsilon_C}{n\epsilon_D} \right] < \theta^* < \frac{n-1}{n-2} \left[\epsilon_C + \frac{n}{n-1} \frac{\epsilon_C}{n\epsilon_D} \right], \; n \geq \bar{n}$$

The long run net effort elasticity of harvest is equal to:

$$\epsilon_c \equiv 1 - \frac{n\hat{e}f'}{r - G' + n\hat{e}f'}$$

Proof. See Appendix. ∎

This result has intuitive appeal. First, when the number of firms tends toward infinity then $\theta^* \to 0$ as $\epsilon_c \to 0$ when $n \to \infty$; second, by definition of $\bar{n}$, $\theta^* = 1$ when $n = \bar{n}$; third, no level of property rights completeness induces the Pareto optimal level of activity by a monopoly; fourth and most importantly, when the number of firms is not lower than $\bar{n}$, the level of property right completeness θ^* induces Pareto optimal behavior by the industry. As will be explained further below, ϵ_c can be regarded as a measure of the common-access externality whereas $\frac{1}{\epsilon_D}$, the Lerner index, measures market power. Equation (18) provides that the optimal completeness level of property rights must be such that those two inefficiencies offset each other.

5.2 Policy implications

As documented earlier in Section 4, there are many practical situations where property rights are incomplete, whether they arose endogenously or result from policy design. A well known example that has drawn the attention of fishery economists is when complete fishing rights are defined on a share of the biomass, the rest being in common access. This happens in particular when the biomass habitat extends beyond the geographic zone subject to regulation. If the relevant fishery is homogenous as assumed in the above analysis, the model then applies as formulated and θ is the ratio of the free access territory over the total habitat of the species. Whether θ can be chosen by the regulator is another issue. If the fish habitat spans national and international waters, the regulated portion may have to remain strictly below unity; even within national waters, other considerations may limit the ability of governments to establish the required institutions. Nonetheless, the above analysis applies whether or not the optimal level of completeness is within the reach of the regulator; the upper boundary constraint may exceed the optimal level and adopting it would imply excessive protection for the oligopoly.

Parameter θ may also reflect incompleteness in the level of protection provided by regulation whether or not regulation covers the integrality of the relevant territory. For example the enforcement system may allow a certain proportion θ of the harvest to go unreported by the industry, or may tolerate excesses over the prescribed limit. In such cases the model also applies directly if the fishery habitat is completely covered. If both incomplete habitat coverage and incomplete protection are present θ must straithforwardly be redefined to take into account both types of incompleteness.

If the issue is poaching, the model applies directly provided the poachers are the same economic agents as the firms that operate in day light. If the poachers are different agents, then the model has to be adapted to allow for two categories of fishermen or more. Even if the numbers in each category are given, their objective functions probably differ, requiring modifications to the model. In any case the underlying intuition, that market power must be offset by weaker rights, would still apply.

Given that parameter θ can be empirically defined and measured in many practical situations, the next issue is whether Expression (18) can be used to determine its optimal level. Here, the answer is a cautious yes. The number of firms in the industry is normally known. Demand elasticity is a well understood concept, although some difficulties might arise defining the proper market. The last element entering the formula is the long run net effort elasticity of harvest. It may be measured by direct observation; this is difficult though, as it requires data on long run (steady state) harvests at different effort levels. An alternative way to measure ϵ_C is to use the formula given in Proposition 2. This expression involves the number of firms, the harvest technology $h = ef$, and the biomass growth function G, evaluated at the desired steady state. Such information might be considered very difficult to obtain. However, the same information is necessary to determine quotas or catch limits and such regulations are routinely used. The use of Proposition 2 and of the formulas it involves has the same policy relevance and involves the same informational requirements as regulatory decisions involving quotas or catch limits.

5.3 Dynamic considerations

The fishery model presented above is widely used to study the interaction of human harvest activity with biological growth over time. Its welfare and dynamic properties have been studied extensively. The Pareto optimal trajectory over time of the fish population and harvest are characterized by the method and expressions briefly summarized in Subsection 3.2. It converges toward the steady state equilibrium described by (10). It is also well established that perfect competition with complete property rights ($n \to \infty;\ \theta = 0$) also yield that Pareto optimal trajectory, while monopoly ($n = 1\ \forall\ \theta$) implies a qualitatively similar trajectory with convergence to a higher biomass level, and perfect competition without property rights ($n \to \infty;\ \theta = 1$) causes convergence to a lower biomass level.

Why restrict the analysis to steady state situations when $0 < n < \infty$? Because no general version of the model addresses game theoretic situations such as oligopoly. Only highly restricted models have been solved as Markov perfect[21] or even open loop dynamic games because of technical difficulties described in Dockner et al. (2000).[22] On the other hand a static version of the fishery model, sometimes used for its simplicity, replaces the external effect of fishing on biomass growth with a static congestion externality. Unfortunately, it prescribes an erroneous optimal biomass level because it ignores the opportunity cost for society of holding a stock of valuable biomass over time.[23] For that reason, despite the fact that the analysis is restricted to steady state situations in this paper, it is preferable to characterize these steady states on the basis of the truly dynamic model.

Recently, Costello et al. (2015) analyzed a discrete dynamic spatial fishery model involving property right incompleteness. Its assumptions imply that adjustment to the steady state occurs within one period. As a result, although the model is very different from ours and is solved as a dynamic problem, it only allows to compare steady state situations for alternative institutions as we do here.[24]

To sum up we use a dynamic version of the fishery model to base our analysis on a well founded and general characterization of the steady state biomass and the corresponding harvest. This is a prerequisite for policy relevance. We confine the analysis to steady states of that model because this allows us to rely on the standard static solution concept of the Nash oligopoly, avoiding the severe restrictions necessary to explicitly find a Markov perfect solution to the dynamic version of the oligopoly game. Proposition 2 gives the level of property rights completeness under which the steady state equilibrium is Pareto optimal.

[21] Lehvari and Mirman, 1980 provide a famous early example of such a game.

[22] Indeed these authors describe a fishery model (pages.331-33) whose special benefit function assigned to N symmetric fishermen allows them to find a Markov perfect Nash equilibrium for the non cooperative game played by the fishermen. However that benefit function does not allow to disentangle the role of demand, the harvest technology, and property rights in the determination of the equilibrium harvest trajectory and its steady state.

[23] The biomass level defined as Pareto optimal in the static version of the model only coincides with the steady state Pareto optimum level given by (9) if the discount rate is nul. See Footnote 3.2.

[24] The authors also assume that the firms that enjoy property rights adopt a cooperative behavior in the regulated territory, thus avoiding the gaming situation associated with oligopoly that we examine here.

What are the implications for out of steady state equilibrium situations? As just mentioned the existing theoretical literature (let alone the empirical literature) does not provide any explicit description of the exact trajectory by which oligopolistic firms arrive at a steady state equilibrium, not matter their institutional environment. What we know from the above analysis is that the oligopolistic steady state biomass level toward which it must converge can be made to coincide with the Pareto optimal biomass level by setting $\theta = \theta^*$, provided the number of firms is not lower than $\bar{n}$. From a practical point of view, if Expression (18) is implemented using data that do not reflect the steady state equilibrium at wich ϵ_c and ϵ_D should be measured, the fishery will approach a different steady state, hopefully closer to efficiency, until the data is improved by new measurements. Similar adjustments are necessary whenever ITQ's or other quotas and allowable catches are imposed.

5.4 The role of tastes, technology, biology, and the number of firms

Proposition 3 *Everything else the same, the more price elastic market demand, the more complete optimal property rights need to be; the higher the long run net effort elasticity of production, the weaker optimal property rights need to be; the greater the number of firms, the more complete optimal property rights should be.*

Proof. $\frac{\partial \theta^*}{\partial \epsilon_D} = \frac{-\epsilon_c}{(n-1){\epsilon_D}^2} < 0$ as $\epsilon_c > 0$ and $n > 1$.
$\frac{\partial \theta^*}{\partial \epsilon_c} = 1 + \frac{1}{(1-n)\epsilon_D} > 0$.
$\frac{\partial \theta^*}{\partial n} = \frac{-1}{(n-1)^2}\frac{\epsilon_c}{\epsilon_D} < 0$. ■

The higher the market power of oligopolistic firms, the more partial optimal property rights must be to ensure production at optimal level. Using the definition of ϵ_c, we can write $\left.\frac{\partial H}{\partial e_i}\right|_{E^*,S^*} = \epsilon_c\left(\frac{H^*}{E^*}\right)$. Therefore, ϵ_c can be regarded as a measure of the distance between average product $\frac{H^*}{E^*}$ and marginal product $\left.\frac{\partial H}{\partial e_i}\right|_{E^*,S^*}$. As $\epsilon_c < 1$, the higher ϵ_c, the closer the average and marginal products are (i.e. the weaker is the intensity of the commons problem), the more partial property rights must be to ensure production at optimal level. The distance between average and marginal costs will be greater in industries with significant economies of scale. In those industries, our results suggest that stronger (although partial) property rights are necessary to offset market power.

The relationship between the number of firms and the optimal strength of property rights illustrates Hotelling's Scylla and Charybdis dilemma:[25] institutions that allow firms to wield market power must also be characterized by the incompleteness of their property rights (hence taming oligopolistic behavior).

Evidence on the balance that needs to be maintained between market power and exclusion can take several forms. The next corollary focuses on the relationship between the cost of market inputs and the market value of output.

Corollary 2 *Everything else the same, the lower the ratio between market input costs and the market-value of output, the stronger optimal property rights need to be.*

Proof. We have $\epsilon_c = \frac{dH^*}{dE}\frac{E}{H}$.Using Condition (9), the long run net effort elasticity of production can be rewritten as $\epsilon_c = \frac{E^*}{H^*}\frac{w}{P(H^*)}$, the ratio of input costs over harvest market value. Since $\frac{\partial \theta^*}{\partial \epsilon_c} > 0$, the result follows. ■

A low ratio of input costs over output market value identifies high rents. These rents are a mixture of market rents and resource rents. However, given that demand elasticity identifies market rents, the higher the ratio of $P(H^*)H^*$ over wE^* given ϵ_D, the higher the rents from exploiting the resource, the greater the potential commons problems, hence the more complete property rights must be. Valuable scarce resources need to be protected by strong (although partial) property rights. Demsetz (1967) argues that, in a competitive economy, property rights develop to internalize externalities. Here, in presence of market power, efficient property rights also need to be stronger when resource rents are higher.

[25] Hotelling (1931) writes:

> "The government of the United States under the present administration has withdrawn oil lands from entry in order to conserve this asset, and has also taken steps toward prosecuting a group of California oil companies for conspiring to maintain unduly high prices, thus restricting production. Though these moves may at first sight appear contradictory in intent, they are really aimed at two distinct evils, a Scylla and Charybdis between which public policy must be steered."

The impact of efforts on harvest is a characteristic of the harvest technology and depends on the role of the biological input in that technology. In turn, harvesting has an impact on the resource stock, and that impact depends on the biological characteristics of the resource. These elements combine to characterize the sensitivity of the resource to open access and the need of protection by property rights as indicated in the next corollary.

Corollary 3 *The effort elasticity of harvest can be decomposed as:*

$$\epsilon_c = \omega_c + \eta_c \varsigma_c$$

where $\omega_c = \frac{E^*}{H^*}\frac{\partial h}{\partial e_i}(e^*(n), S^*)$ *is the partial effort elasticity of harvest at* (E^*, H^*), $\eta_c = \frac{E^*}{S^*}\frac{\partial S}{\partial e_i}(e^*(n), S^*)$ *is the effort elasticity of the resource stock at* (E^*, S^*) *and* $\varsigma_c = \frac{S^*}{H^*}\sum_{j=1}^{n}\frac{\partial h}{\partial S}(e_j^*(n), S^*)$ *is the resource stock elasticity of production at* (S^*, H^*).

Everything else the same, the higher the direct impact of efforts on harvest, the more partial optimal property rights must be; and the more negative the total effort elasticity of the resource stock, the more complete optimal property rights must be.

Proof. $\epsilon_c = \frac{E^*}{H^*}\frac{dH^*}{dE^*}$ can be rewritten as:

$$\epsilon_c = \frac{E^*}{H^*}\frac{\partial h}{\partial e_i}(e^*(n), S^*) + \left(\frac{E^*}{S^*}S'(E^*)\right)\left(\frac{S^*}{H^*}\sum_{j=1}^{n}\frac{\partial h}{\partial S}(e_j^*(n), S^*)\right)$$

Call $\omega_c = \frac{E^*}{H^*}\frac{\partial h}{\partial e_i}(e^*(n), S^*)$ the partial effort elasticity of harvest at (E^*, H^*), $\eta_c = \frac{E^*}{S^*}S'(E^*)$ the effort elasticity of the resource stock at (E^*, S^*) and $\varsigma_c = \frac{S^*}{H^*}\sum_{j=1}^{n}\frac{\partial h}{\partial S}(e_j^*(n), S^*)$ the resource stock elasticity of production at (S^*, H^*). We have:

$$\epsilon_c = \omega_c + \eta_c \varsigma_c$$

As $\varsigma_c > 0$ and $\eta_c < 0$, given that ϵ_c affects θ^* positively, the results follow. ■

6 Conclusion

Pareto optimality in the exploitation of natural resources such as fisheries may require incomplete property rights even in the absence of definition or enforcement costs. The

Pareto optimal level of incompleteness will strike a balance between incentives to overexploitation caused by too easy access to the resource, and incentives to restrict supply present when the number of actors is limited. Although market power is sometimes dismissed as irrelevant in an intellectual climate dominated by the tragedy of the commons, it was present in fisheries before overexploitation became an issue, and may be or may become a problem in many contemporary situations where regulation and the creation of institutions promoting efficiency may result in limitations to the number of fishermen.

Property rights regimes observed in some Nova Scotia fisheries, in some New Zealand ITQ regimes or in the South Pars/North Dome gas field and often dismissed as imperfect because they provide only partial protection, may thus be closer to optimality than widely believed. More significantly, regulators and analysts should not consider complete property rights as perfect.

Instead, this paper provides a formula giving the optimal level of property right incompleteness on a scale of zero to one. Depending on the actual context, this level of incompleteness may correspond to the proportion of fish territory left under free access relative to the total biomass territory; it may also measure the tightness of the enforcement system and the tolerance to poaching.

The efficient level of property right incompleteness is given by a formula involving well defined and measurable data: the number of firms, demand elasticity, and the effort elasticity of harvest, where effort stands for the combination of fishing inputs other than the biomass itself. Greater demand elasticity requires more complete property rights.

Technology and biology are also important determinants. The optimal completeness level depends on the value of output relative to non resource (typically market) production inputs: the more valuable is the output compared to the input, the greater the profits, the more intense is the commons problem and the stronger property rights must be. Similarly, from a biological point of view, if the stock of resource is more sensitive to harvesting efforts, that is if the fish are easy to catch considering their value, optimal property rights must be more complete.

Common sense and observation indicate that real world fisheries are often overexploited but are resilient enough to have survived. Unless their economic, institutional or physical environment is changing rapidly, this means that they are observed in situations that are not far removed from steady state equilibria, however dismal such equilibria may be. Consequently the analysis presented in this paper, confined to steady state situations as it is, is relevant to many fisheries where property rights are needed to alleviate the tragedy of the commons or must be tamed to compensate for market power. Nonetheless, a generalization of the analysis to situations away from steady states would be welcome. Although the literature on dynamic games indicate that such an extension is an ambitious prospect, the intuition underlying this paper, that property rights need to be partial in order to create a balance between overexploitation due to free access, and undersupply due to the exercise of market power, is likely to apply in states other than the steady state equilibrium.

Beyond its immediate relevance to fishery economics, it should be clear that our analysis can be adapted to many circumstances where, for the well being of society, excessive power in the hands of some economic agents should be compensated by less than complete property rights protecting these agents.

APPENDIX: Proof of Proposition 2

The first-order condition (13) for Nash equilibrium in steady state for firm i is $f\left\{\left[\beta_i + \Psi(e_i, \sum_{j\neq i}^{n} e_j)\theta\right][P'H + P] + \Psi_{e_i}(e_i, \sum_{j\neq i}^{n} e_j)\theta EP - m_i\right\} = w$. At the symmetric Nash equilibrium, $e_i = \hat{e}\ \forall i$, $\beta_i = \beta = \frac{1-\theta}{n}$; $m_i = m$; $\hat{E} = n\hat{e}$, $\hat{S} = S(\hat{E})$, and $\Psi\left(e, (n-1)\,e\right) = \frac{1}{n}$ so that:

$$f\left\{\frac{1}{n}\left[P'n\hat{e}f + P\right] + \Psi_{e_i}(\hat{e}, (n-1)\,\hat{e})\theta n\hat{e}P - m\right\} = w$$

Furthermore, in symmetric steady state by (14),

$$m = P\left[1 - \frac{1}{\epsilon_D}\right]\frac{\hat{e}f'}{r - G' + nef'}$$

where $\epsilon_D \equiv \frac{-dH}{dP}\frac{P}{H}$ with $H = nef$. This is to be compared with the resource shadow value for society $\mu = P\frac{n\hat{e}f'}{r-G'+n\hat{e}f'}$; $m = \mu$ if $n = 1$ and $P' = 0$; otherwise $m < \mu$ provided $r - G' < 0$, which is the case in equilibrium. Thus in symmetric Nash equilibrium (13) reduces to:

$$f\left\{\left[P'\hat{e}f + \frac{1}{n}P\right] + \Psi_{e_i}(\hat{e}, (n-1)\,\hat{e})\theta n\hat{e}P - P\left[1 - \frac{1}{\epsilon_D}\right]\frac{\hat{e}f'}{r - G' + \_nef'}\right\} = w$$

We look for a condition ensuring that $\widehat{e}(\theta, n) = e^*$ for some $\theta = \theta^*$. If θ^* exists, it must ensure that the left hand side of the above expression (i.e. $\Gamma(\widehat{e}, n, \theta)$) equals the left hand side of (9) when $\hat{e} = e^*$:

$$f\left\{\left[P'\hat{e}f + \frac{1}{n}P\right] + \Psi_{e_i}(\hat{e}, (n-1)\,\hat{e})\theta n\hat{e}P - P\left[1 - \frac{1}{\epsilon_D}\right]\frac{\hat{e}f'}{r - G' + nef'}\right\} = P\left[1 - \frac{n\hat{e}f'}{r - G' + n\hat{e}f'}\right]f$$

$$\left[P'\hat{e}f + \frac{1}{n}P\right] + \Psi_{e_i}(\hat{e}, (n-1)\,\hat{e})\theta n\hat{e}P - P\left[1 + \left(1 - n - \frac{1}{\epsilon_D}\right)\frac{\hat{e}f'}{r - G' + nef'}\right] = 0$$

Dividing by P gives:

$$\frac{P'}{P}\hat{e}f + \frac{1}{n} + \Psi_{e_i}(\hat{e}, (n-1)\,\hat{e})\theta n\hat{e} - 1 - \left[1 - n - \frac{1}{\epsilon_D}\right]\frac{\hat{e}f'}{r - G' + n\hat{e}f'} = 0$$

$$\frac{-1}{n\epsilon_D} + \frac{1}{n} + \Psi_{e_i}\theta n\hat{e} - 1 + \left[\frac{1}{n} - 1 - \frac{1}{n\epsilon_D}\right]\frac{n\hat{e}f'}{G' - n\hat{e}f' - r} = 0$$

$$\Psi_{e_i}\theta n\hat{e} - \left(1 + \frac{n\hat{e}f'}{G' - n\hat{e}f' - r}\right) + \frac{1}{n}\left(1 + \frac{n\hat{e}f'}{G' - n\hat{e}f' - r}\right) - \frac{1}{n\epsilon_D}\left(1 + \frac{n\hat{e}f'}{G' - n\hat{e}f' - r}\right) = 0$$

$$\Psi_{e_i}\theta n\hat{e} - \epsilon_C\left(\frac{n-1}{n} + \frac{1}{n\epsilon_D}\right) = 0$$

where $\epsilon_C \equiv 1 + \frac{n\hat{e}f'}{G' - n\hat{e}f' - r}$ and will be given an interpretation further bellow. It follows that:

$$\theta = \frac{1}{n\hat{e}\Psi_{e_i}} \epsilon_C \left(\frac{n-1}{n} + \frac{1}{n\epsilon_D} \right) \tag{19}$$

For example, if $\Psi(e_i, \sum_{j\neq i}^n e_j) = \frac{e_i}{e_i + \sum_{j\neq i}^n e_j}$, then $E\Psi_{e_i}(e, (n-1)e) = ne\frac{1}{e}\frac{n-1}{n^2} = (n-1)/n$ so that (18) holds exactly:

$$\theta = \epsilon_C + \frac{n}{n-1}\frac{\epsilon_C}{n\epsilon_D}$$

General forms of Ψ satisfying Assumption 1. Since $n \geq \bar{n} > 1$, consider $n \geq 2$ with $e_i = e_j = e > 0$ and $E = (n-1)e$. For $n = 2$, $\Psi(e, E) = \Psi(e, (2-1)e) = \frac{1}{2}$; by Assumption 1 #3, $\Psi(e, (2-1)e) = \Psi(\frac{3-1}{2-1}e, \left(\frac{3-1}{2-1}\right)(2-1)e) = \frac{1}{2}$; or $\Psi(\frac{3-1}{2-1}e, (3-1)e) = \frac{1}{2}$; for $n = 3$, $\Psi(e, (3-1)e) = \frac{1}{3}$. Hence, for an approximation of $\Psi_e(e, (2-1)e')$ between e and $\frac{3-1}{2-1}e$, we have $\Psi(\frac{3-1}{2-1}e, (3-1)e) - \Psi(e, (3-1)e) = \frac{1}{2} - \frac{1}{3}$ or $\Psi_e(e, (3-1)e)\left(\frac{3-1}{2-1} - 1\right)e \simeq \frac{1}{2} - \frac{1}{3} + \frac{1}{2}\Psi_{ee}\left(e - \frac{3-1}{2-1}e\right)^2 + hot$, where *hot* represents terms of higher than second order and $\Psi_{ee} < 0$ by 1#5. Thus $\Psi_e(e, (3-1)e)\frac{3-1-2+1}{2-1}e > \frac{1}{2} - \frac{1}{3}$ **or** $\Psi_e(e, (3-1)e)e\frac{1}{2-1} > \frac{1}{2*3}$. Doing this derivation for any n gives $\Psi_e(e, (n-1)e)e > \frac{n-1-1}{(n-1)*n}$, from which $\Psi_e(e, (n-1)e)ne > \frac{n-2}{n-1}$;

Alternatively, using Assumption 1 #3 for $n = 3$, i.e. with $\Psi(e, (3-1)e) = \frac{1}{3}$, gives $\Psi(\frac{2-1}{3-1}e, \frac{2-1}{3-1}(3-1)e) = 1/3$; $\Psi(\frac{2-1}{3-1}e, (2-1)e) = 1/3$; hence $\Psi(\frac{2-1}{3-1}e, (2-1)e) - \Psi(e, (2-1)e) = 1/3 - 1/2$; thus $\Psi_e(e, (2-1)e)\left(\frac{2-1}{3-1} - 1\right)e \simeq \frac{1}{3} - \frac{1}{2} + \frac{1}{2}\Psi_{ee}\left(e - \frac{3-1}{2-1}e\right)^2 + hot$; thus $\Psi_e(e, (2-1)e)\frac{1}{3-1}e < \frac{1}{2} - \frac{1}{3}$ or $\Psi_e(e, (2-1)e)e\frac{1}{3-1} < \frac{1}{2*3}$. Doing this for any n gives $\Psi_e(e, (n-1)e)\frac{e}{n} < \frac{1}{(n+1)*n}$, from which $\Psi_e(e, (n-1)e)ne < \frac{n}{n+1}$.

Using the above two inequalities gives

$$\frac{n-2}{n-1} < \Psi_e(e, (n-1)e)ne < \frac{n}{n+1} \tag{20}$$

which further implies that $\frac{n-1}{n}$ is an approximation for $\Psi_e(e, (n-1)e)ne$ and that $\lim_{n\to\infty}\Psi_e(e, (n-1)e)ne = \lim_{n\to\infty}\frac{n-1}{n} = 1$.

Substituting the left hand side of (20) for $n\hat{e}\Psi_{e_i}$ into (19) implies

$$\theta < \frac{n-1}{n-2}\epsilon_C \left(\frac{n-1}{n} + \frac{1}{n\epsilon_D} \right)$$

$$\theta < \frac{(n-1)^2}{(n-2)n}\epsilon_C + \frac{n-1}{n-2}\frac{\epsilon_C}{n\epsilon_D}$$

Similarly substituting the right hand side of (20) for $n\hat{e}\Psi_{e_i}$ into (19) implies

$$\begin{aligned} \theta &> \frac{n+1}{n}\epsilon_C \left(\frac{n-1}{n} + \frac{1}{n\epsilon_D} \right) \\ \theta &> \frac{(n+1)(n-1)}{n^2}\epsilon_C + \frac{n+1}{n}\frac{\epsilon_C}{n\epsilon_D} \end{aligned}$$

Combining the two inequalities gives

$$\frac{n+1}{n}\frac{n-1}{n}\epsilon_C + \frac{n+1}{n}\frac{\epsilon_C}{n\epsilon_D} \quad < \quad \theta < \frac{n-1}{n-2}\frac{n-1}{n}\epsilon_C + \frac{n-1}{n-2}\frac{\epsilon_C}{n\epsilon_D}, \text{ or, dividing by } \frac{n-1}{n}$$

$$\frac{n+1}{n}\left[\epsilon_C + \frac{n}{n-1}\frac{\epsilon_C}{n\epsilon_D}\right] \quad < \quad \theta < \frac{n-1}{n-2}\left[\epsilon_C + \frac{n}{n-1}\frac{\epsilon_C}{n\epsilon_D}\right]$$

which defines the accuracy of (18) if it is used as approximation for (19).

Interpretation of ϵ_C. The marginal effect of an increase in E on the steady state Pareto optimal equilibrium harvest, net of the resource cost, is given by the left hand side of Condition (9) divided by P:

$$\frac{dH}{dE} = \left[1 - \frac{Ef'(S)}{r - G'(S) + Ef'(S)}\right] f(S)$$

Hence the long run net effort elasticity of harvest is $\frac{dH}{dE}\frac{E}{H} = \left[1 - \frac{Ef'(S)}{r-G'(S)+Ef'(S)}\right] f(S)\,\frac{E}{Ef(S)}$ or $\epsilon_C = 1 - \frac{n\hat{e}f'}{r-G'+n\hat{e}f'}$. ■

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1130, rue Sherbrooke Ouest, bureau 1400, Montréal (Québec) H3A 2M8
Tél. : 514-985-4000 • Téléc. : 514-985-4039
www.cirano.qc.ca • info@cirano.qc.ca

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