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Optimal completeness of property rights on renewable resources in the presence of market power[☆]

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A B S T R A C T

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 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 the 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 imply both a severe potential commons problem and may be the expression of market power; strong property rights limit the commons problem; and their incompleteness offsets market power. Biology also impacts the optimal quality of property rights: when the stock of a resource is more sensitive to harvesting efforts, optimal property rights need to be more complete.

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

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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, and they also provide countless examples of situations where property rights are neither perfectly defined nor completely enforced. As a rule, such situations are considered suboptimal.[1]

The basic idea at the root of this 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 idea already present in Hotelling (1931). Nonetheless, incompleteness in property rights is overwhelmingly considered an imperfection, although sometimes this imperfection is a sensible justification such as enforcement costs[2] 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 the 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. This 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 the goal as function of observable variables. Besides identifying empirical circumstances under which the model applies, this paper refers to several studies 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 of their degree of completeness will both depend on the number of actors and affect that number.

Empirically, market power was a feature of some fisheries before fish stock abundance 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 Individual Transferable Quotas, ITQs] 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, 1991). "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 behaviour; 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

[1] 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."

[2] In the 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).

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 this paper is organized as follows. In the next section, we examine the literature. Section 3 presents the biological and technological features of the model, and Section 4 characterizes its efficient steady-state equilibrium. Property rights (Section 4.1) are modelled in such a way that their level of completeness is expressed by a single parameter that varies between zero and one 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 they take other firms harvest decisions as given. Having characterized the resulting steady-state equilibrium in Section 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. In Section 5.1 we find an explicit formula for that optimal completeness level. In Sections 5.2 and 5.3, we discuss policy relevance and dynamic issues, and we explain how the optimal completeness level depends on tastes, biology, technology, and the number of firms in Section 5.4. Section 6 recapitulates and presents a conclusion.

2. Relation to the literature

The early economic literature examines the effects of market power on the exploitation of renewable resources (Scott, 1955, is a classical reference) or on the exploitation of non renewable resources (Salant, 1976; Loury, 1986) in the 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[3] are at the root of the problem caused by the absence of private property rights (e.g., Gordon, 1954; 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; Karp, 1992; Datta and Mirman, 1999; 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 the 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 showed 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 studied the effect of insecure ownership on ordinary investment and natural resource use. They treated the degree of property-rights completeness as exogenous and did not question the desirability of completely secure rights. Several papers involving trade and natural resources have treated the completeness of property rights as endogenous (Hotte et al., 2000; Copeland and Taylor, 2009; Tajibaeva, 2012); they did so without questioning the desirability of completeness. Hotte et al. (2000) considered a small, price-taking, economy in which trade can lead to more complete property rights and a higher level of resource stock at the steady state, but may result in welfare loss due to the existence of enforcement costs. Tajibaeva (2012) also emphasized the importance of enforcement costs. In Copeland and Taylor (2009), property rights were incomplete because of monitoring problems; complete protection of the resource is 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 the presence of market power.

Engel and Fisher (2008) were also concerned with efficiency. However, they did not consider a decentralized economy. They studied 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 considered the impact of expropriation in the presence of uncertainty, market power, and an irreversible fixed cost. Costello and Kaffine (2008) adopted a similar contractual approach. They studied 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 showed that complete property rights are sufficient for economically efficient harvest but are not necessary. They further showed 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 growth rate. They concluded by saying that the "next steps in this vein could include combining the appropriator's incentives with the

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

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.[4]

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 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 $i = 1, \ldots, n$ 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, 1976), 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 the 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 $S > 0$.[5]

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

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

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.[6]

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 we will show.

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

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

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

[5] 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).

[6] 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 when the fishing effort is higher, which means that $\frac{\partial S}{\partial e_i} < 0$. Consequently a sufficient condition for $\frac{dh_i(e_i,S(V))}{de_i} > 0$ is for the equilibrium biomass $S(V)$ to exceed the Maximum Sustained Yield level MSY as $\frac{\partial h_i(e_i,S(V))}{\partial S} < 0 \quad \forall S > MSY$.

so that:

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

Given the biomass, total harvest only depends on total effort. As a result, the steady-state biomass only depends on total effort.[7] We define the steady-state harvest and biomass corresponding to that special case of (3) with identical constant returns technologies as

$$H(E) = Ef(S(E))\,\text{and}\,S(E) \equiv \tilde{S}(V) \tag{6}$$

Eq. (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 $\sum_{i=1}^{n} (P(H)h(e_i, S) - e_i w)$. With identical constant return technologies, this equals $(P(H)f(S) - w)E$. The instantaneous social welfare function is thus $W(H, E) = U(H) - wE$ with $U'(H) = P(H)$. 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:

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

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

The current-value Hamiltonian may be written as

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

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:

$$\dot{\mu} = -(P(H) - \mu)Ef'(S) + \mu\left(r - G'(S)\right)$$

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

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

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

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

where H and S are functions of E given by (6).[8] 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).

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[7] 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).

[8] 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 $r = 0$, $P(H)\left[f(S) + ES'f'(S)\right] = w$.

Assuming that the second-order condition is satisfied,[9] (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:

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

Although the total effort level is determined, its repartition across firms is undetermined.[10] One particular solution is $e_1^*(n) = e_2^*(n) = \cdots = e_n^*(n) = e^*(n)$ with $e^*(n) = \frac{E^*}{n}$. 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),[11] 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 four characteristics, each one to the fullest possible extent.[12] This paper focuses on exclusivity, assuming that the other three characteristics are all present to the fullest extent if a right is present at all. Exclusivity will be present at various degrees of completeness.

In order for 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 that 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 migrate 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. They provide output appropriation—the owner gets the benefit from her production—and they provide input exclusion—an input is used exclusively by or for the benefit of its owner. Hotte et al. (2013) considered issues of input exclusion and output appropriation simultaneously. They showed 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, is 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 ITQs 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 fish inputed to the quota and the resource input used, which takes the form of fish taken out of the water.

If the right is incomplete, the number of fish taken out of the water is higher than the total number of fish 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 ITQs 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) provided an illustration of such systems in Nova Scotia. The authors describe a rights-based fishery management system in which the ITQ on a share of the total allowable catch ("TAC") coexists with a non-ITQ competitive fishing pool on the remaining share of the TAC.

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

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

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.

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

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

[12] 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 Ostrom and Schlager (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.)."

Hannesson (2004) and Stavins (2011) provided other illustrations mentioning fish species that migrate between exclusive economic zones—200 miles from coastlines—that are 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) gave 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.[13] 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 ensuring 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 this 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. It is convenient to think in terms of ITQs. 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 rights models the situations evoked above fairly well. For example if ITQs 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 ITQs while θ is the proportion under common access. The firms complement their quotas by harvesting in the common access zone.[14] 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 $\left(1-\theta\right)G(S)$ is effectively allocated in the form of ITQs while a quantity $\theta G(S)$ evades 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 and they will not benefit from their restraint. So this part of their objective function is modelled as common access as described just below.

Firms compete for the part of the resource that 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 of 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:

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

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; and 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:

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

[13] 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.

[14] 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.

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 $\beta_i G(S)$, i.e. 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). Using (11), the current-value Hamiltonian is:

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

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

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

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

This condition expresses the equality of marginal revenue (net of the marginal biomass cost $m_i f(S)$) with marginal cost of effort w. It is most easily understood if one considers the particular case of monopoly exploitation, where $\beta_i = 1$ and, since no other firms have access to the resource, $\theta = 0$. The formula reduces to $f(S)\left\{[P'(H)H + P(H)] - m_i\right\} = w$. 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.[15]

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

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

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

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

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 Eq. (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 unit effort, net of the biomass cost m_i as 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 Eqs. (13), (14), (6) depends on n, on θ, and on the combination of shares β_i.[16] 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 Eq. (13) is the same effort level. At the symmetric steady-state Nash equilibrium, the level of input extended by each firm $\hat{e}(\theta; n)$ is then implicitly defined by:

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

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

Eq. (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.

[15] Condition (13) also differs from (7) in that the shadow price of the resource m_i chosen by a monopoly generally 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.

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

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) implies the same effort level as condition (9) which characterizes the 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 commons. 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 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 $\bar{n}\hat{e}(1;\bar{n}) = E^*$.

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 $\Gamma(\hat{e}, n, \theta) = \left\{[P'H+P]\frac{1}{n} - [P'H+P]\frac{1}{n}\frac{nef'}{r-G'+nef'} + yP\Psi_e ne\right\} f$. Thus $\Gamma(\hat{e}, n, \theta)$ coincides with the left-hand side of (9) (where $E = n\hat{e}$, $S = S\left(n\hat{e}\right)$, and $H = n\hat{e}f(S\left(n\hat{e}\right))$) if the following condition is satisfied when $n = \bar{n}$:[17]

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

One notes that, for any level of e such that $ne = E^*$, the left-hand side of (16) is smaller 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 left-hand side then vanishes while $\Psi_e n\hat{e}$ must tend toward one 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.[18] 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: $n\hat{e}(\theta^*; n) = E^*$.*

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

The Pareto-optimal number of firms $\bar{n}$ in pure common-access verifies the condition $\bar{n}\hat{e}(1;\bar{n}) = E^*$. By (16) (and as shown by Cornes et al., 1986 for the static congestion model) 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: $\hat{e}(1;n) > e^*(n), \forall n > \bar{n}$. Hence:

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

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

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

Because $\hat{e}(\theta; n)$ 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:

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

□

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. This result follows from $n\hat{e}(1;n) > E^*$ and $n\hat{e}(0;n) < E^*, \forall n > \bar{n}$. □

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[17] 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.

[18] 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.

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. By Proposition 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 $\hat{e}(\theta; n)$ 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:*

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

where ϵ_D is the price elasticity of market demand in absolute value and ϵ_C is the long-run 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:

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

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

$$\epsilon_C \equiv 1 - \frac{n\hat{e}f'}{r - G' + n\hat{e}f'} \tag{19}$$

Proof. See Appendix. □

This result has intuitive appeal. First, when the number of firms tends toward infinity then $\theta^* \to 0$ (as $n\hat{e}$, hence also ϵ_C, are independent of n); 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. Eq. (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 known example that has drawn the attention of fishery economists is when complete fishing rights are defined on a share of the biomass, with 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 one; 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 regulations whether or not they cover 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 straigthforwardly be redefined to take into account both types of incompleteness.

If the issue is poaching, the model applies directly as long as the poachers are the same economic agents as the firms that operate legitimately. 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 effort elasticity of harvest. It may be measured by direct observation, although this is difficult because 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 by the expressions that are briefly summarized in Section 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 the Pareto optimal trajectory, while monopoly $\left(n = 1 \quad \forall \quad \theta\right)$ 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[19] or even open-loop dynamic games because of technical difficulties that are described in Dockner et al. (2000).[20] 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.[21] 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 the comparison of steady-state situations for alternative institutions as we do here.[22]

To sum up we use a dynamic version of the fishery model so as 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.

What are the implications for situations that are not steady-state equilibria? 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, regardless of 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 which ϵ_C and ϵ_D should be measured, the fishery will approach a different steady state, hopefully closer to efficiency, until the data are improved by new measurements. Similar adjustments are necessary whenever ITQs or other quotas and allowable catches are imposed.

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

We have analyzed and clarified the mechanism underlying the efficiency trade-off between market power and the level of property right completeness. Perfect competition, involving numerous agents of negligible size relative to the market, is desirable when property rights are complete. However, competition is a *tragic* nuisance under weak property rights; complete rights are desirable when perfect competition prevails. Proposition 2 specifies the desirable level of completeness in situations ranging from high market power to perfect competition.

[19] Levhari and Mirman, 1980 provide a famous early example of such a game.

[20] Indeed these authors describe a fishery model (pp. 331–333) 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 one to disentangle the role of demand, the harvest technology and property rights in the determination of the equilibrium harvest trajectory and its steady state.

[21] 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.

[22] 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.

Empirical evidence on market power in fisheries is scant considering the abundance of the theoretical literature on the subject. Few major papers were published since Graddy's (1995) *Testing for Imperfect Competition at the Fulton Fish Market*. Discussions are often cast in terms of equity rather than efficiency. One reason is certainly that few valuable fisheries have escaped the tragedy of the commons or gone a long enough way toward recovery, so that damage from competition remains tangible and fresh in memories while damage from market power is not perceived with the same urgency.[23]

Another reason is that market power in a resource industry is much more difficult to identify than in conventional sectors. This is because any rent arising from market power is difficult to disentangle from the resource rent that coexists with it. Both rents contribute to drive a wedge between price and marginal cost, so that the mere fact that price exceeds marginal cost is not necessarily a sign of market power in a well-managed resource industry.[24]

Nonetheless, some evidence of market power exists, whether anecdotal (Manning, 2015) or scientific and sometimes mixed (North Atlantic cod: Newell et al., 2005; Bergmann, 2014; Xie, 2015; Blomquist, 2015; European fish markets: Simioni et al., 2013; Malaysia: Omar, 1995; Australian coral reef fin fish: Innes et al., 2014). The North American lobster is sometimes given as an example of an integrated and highly competitive market (e.g., Gardner, 2011) because many US and Canadian fishermen basically sell on a single US market that also supplies the world (Gulf countries and Japan in particular). Yet, "In the summer and fall New England has the power to influence lobster prices as the Canadian harvest is closed. In the winter and spring, Canada is empowered to exert pricing pressures as their season is in full swing" (Lobster Coast, 2012).[25]

As a matter of fact, regulators and stakeholders involved in ITQs are very sensitive to the issue of market power. Consolidation caps are pervasive and can be considered as attempts to maintain the number of active firms. They validate our modelling decision to treat n as exogenous. Precisely, as the proposition presented below makes clear, allowing a lower number of participants would require the rights associated with ITQs to be less complete.[26]

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

Proof. From (18), as $\epsilon_C > 0$, $\epsilon_D > 0$, and $n > 1$;
$\frac{\partial\theta^*}{\partial n} = \frac{-1}{(n-1)^2}\frac{\epsilon_C}{\epsilon_D} < 0$;
$\frac{\partial\theta^*}{\partial\epsilon_D} = \frac{-\epsilon_C}{(n-1)\epsilon_D{}^2} < 0$
$\frac{\partial\theta^*}{\partial\epsilon_C} = 1 + \frac{1}{(n-1)\epsilon_D} > 0$; □

In the present paper, consolidation caps can be viewed as restrictions to property rights imposed before any adjustment to θ. To the extent that they require the number of firms to be large, no restrictions to property rights are necessary: by (18), $\theta^* \to 0$ when $n \to \infty$. However, not all fisheries are large even when consolidation caps restrict their shrinkage, and there is considerable debate about the desirability to allow some fisheries to consolidate into a few more efficient operators. Whatever the reason, further restrictions may be necessary when n is not high, and Proposition 3 also explores the role of factors other than the number of firms—demand elasticity and the long-run effort elasticity.

While the sign of each comparative statics effects is unambiguous, magnitudes depend on several parameters. A reduction in the number of operators does not necessarily call for a reduction in the extent of their rights (an increase in θ). If ϵ_D is very high, the required adjustment to θ^* should be negligible (first comparative statics). This would fit the example of the lobster industry given above. However, if US lobster fishermen succeeded in restricting Canadian imports, it is clear that the appropriate value of ϵ_D would be reduced. Even with a low value of ϵ_D, the expression $\frac{\partial\theta^*}{\partial n}$ implies that, unless the fishermen also managed to escape the non-cooperative framework of this model, perhaps by taking control of the regulator or reinforcing cooperative institutions, their sheer number would keep $\frac{\partial\theta^*}{\partial n}$ very low.

The central argument of this paper implies that the optimal completeness of property rights does not depend on demand elasticity and firm numbers only. It also depends on the biological and the technological elements that underlie the long-run effort elasticity of harvest and may give rise to the tragedy of the commons. Indeed, ϵ_C depends on the fishing technology via f and the fishery's biology via G.[27] Precisely, (8 and 19) imply that $\epsilon_C = \frac{P-\mu}{P}$, thus measuring the magnitude of the resource

[23] As Libecap (2007) puts it, "formal property rights institutions are adopted only late, after conditions have deteriorated for many regulated resources. By that time, political conflict over the assignment of the costs and benefits of a new property regime is swamped by the overall costs of not taking action. Unfortunately, by that time many of the resource rents have been dissipated."

[24] Furthermore, the resource rent under perfect competition with complete property rights is higher than the resource rent in the presence of market power. Compare μ and m given in the appendix.

[25] Our model limits itself to the possibility of non-cooperative market power. However price raising cooperation may be achieved by regulation (e.g., supply management in agriculture) or collective forms of organization. It is interesting to note that the ingredients allowing alleviation of the problem of the commons are the same ones that allow the exercise of market power.

[26] We thank Daniel Kaffine for pointing out this interpretation of consolidation caps.

[27] f gives the marginal increase in individual harvest (by unit effort) associated with the biomass stock (see (5)) and G' is the marginal natural growth of the biomass.

rent μ relative to the price. Hence we see the importance of measuring ϵ_C at the optimal steady-state values of H and E, and not at values that would prevail in a steady state exhibiting rent dissipation. When μ is higher (and ϵ_C lower), the role of property rights becomes more crucial in protecting the resource relative to avoiding the exercise of market power, hence the sign of $\frac{\partial\theta^*}{\partial\epsilon_C}$. Referring again to the lobster example where the resource rent is high (the resource is valuable, easy to catch, and slow to reach maturity), θ^* should be close to zero (close to complete rights) by (18) and show little sensitivity to considerations of market power by the first two comparative statics results of Proposition 3.

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. *When everything else is 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 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 ϵ_D and n, the higher the ratio of $P(H^*)H^*$ over wE^*, the higher the rents from exploiting the resource and the greater the potential commons problems; hence the more complete the property rights must be. Cod is an intermediate example. Like lobster, it is capable of generating substantial rents. However the price must cover significant input costs before leaving room for a rent. Thus ϵ_C is likely to be higher than in the case of lobster, so that market power must be given due consideration when establishing property rights.

The impact of fishing efforts on harvest is a characteristic of the harvest technology and depends on the role of the biomass stock 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:*

$$\epsilon_C = \omega_c + \eta_C\varsigma_C \tag{20}$$

where $\omega_c = \frac{1}{f(S^*)}\frac{\partial h}{\partial e_i}(e^*(n), S^*)$ *is the partial individual-effort elasticity of harvest at* (E^*, H^*), $\eta_C = \frac{E^*}{S^*}S'(E^*)$ *is the total-effort elasticity of the resource stock at* (E^*, S^*), *and* $\varsigma_C = \frac{S^*}{G(S^*)}\sum_{j=1}^n \frac{\partial h}{\partial S}(e_j^*(n), S^*)$ *is the resource stock elasticity of production at* (S^*, H^*).

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

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

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

After substituting $\frac{1}{f(S^*)}$ for $\frac{E^*}{H^*}$ from (5) and $G(S^*)$ for H^*, call $\omega_c = \frac{1}{f(S^*)}\frac{\partial h}{\partial e_i}(e^*(n), S^*)$ the partial individual-effort elasticity of harvest at (E^*, H^*), $\eta_C = \frac{E^*}{S^*}S'(E^*)$ the total-effort elasticity of the resource stock at (E^*, S^*) and $\varsigma_C = \frac{S^*}{G(S^*)}\sum_{j=1}^n \frac{\partial h}{\partial S}(e_j^*(n), S^*)$ 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. □

Expression (20) separates out the role of the fishing technology, which determines the impact of fishing effort and the biomass stock in ω_c and η_C, and the role of the fishery's biology in permitting sustainability as evidenced in ς_C by the ratio of the biomass stock over the steady-state harvest. For example, fast-growing species such as sardines or anchovies exhibit a lower resource stock elasticity of production, thus a lower value of ϵ_C, than relatively slow-growing species such as lobster and cod. They do not need property rights that are as complete.

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 that are 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 it 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 that are observed in some Nova Scotia fisheries, in some New Zealand ITQ regimes, or in the South Pars/North Dome gas field, and that are 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 severity 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 the output is compared to the input, the greater the profits, the more intense the commons problem, and the stronger property rights must be. Similarly, from a biological point of view, if the resource stock is more sensitive to harvesting efforts, i.e., 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 not in steady states would be welcome. Although the literature on dynamic games indicates 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 steady-state equilibria.

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.

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 $\Psi(e,(n-1)e)=\frac{1}{n}$ 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 $m<\mu$. 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 $\hat{e}(\theta,n)=e^*$ for some $\theta=\theta^*$. If θ^* exists, it must ensure that the left-hand side of the above expression (i.e., $\Gamma(\hat{e},n,\theta)$) 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 below. It follows that

$$\theta = \frac{1}{n\hat{e}\Psi_{e_i}}\epsilon_C\left(\frac{n-1}{n} + \frac{1}{n\epsilon_D}\right) \tag{21}$$

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

$$\frac{n-2}{n-1} < \Psi_e(e,(n-1)e)ne < \frac{n}{n+1} \tag{22}$$

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 (22) for $n\hat{e}\Psi_{e_i}$ into (21) 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 (22) for $n\hat{e}\Psi_{e_i}$ into (21) implies

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

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

Combining the two inequalities gives

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

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

which defines the accuracy of (18) if it is used as an approximation for (21).

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 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 $\epsilon_C = 1 - \frac{n\hat{e}f'}{r-G'+n\hat{e}f'}$. $\square$

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