

Natural resource use with limited-tenure property rights

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Abstract

We 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) only if a target stock is achieved. Despite the insecurity of this property right, simple concessions contracts can be designed to induce first best harvest trajectories. We examine how those contracts will depend on economic, ecological, and institutional variables, and apply theoretical insights to two concessions-managed fisheries in Baja California, Mexico.

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0. Introduction

That open access or common pool management can lead to resource overexploitation is well known [14,23]. Equally widely acknowledged is the ability of secure, perpetual, and enforceable property rights to induce efficient resource use [11]. The ability of property rights to help correct resource overexploitation is increasingly being appreciated in policy circles. Yet governing bodies are reluctant to relinquish complete control over public trust resources, and instead often grant to resource appropriators various forms of limited tenure with the possibility of renewal.¹ This raises questions of great practical and theoretical importance: To what extent will introducing limitations or uncertainty to a property right alter incentives for resource use? Could this offset some (even all) of the benefits of assigning rights in the first place? Are insecure rights and economically efficient resource use mutually exclusive? If not, what must the design of insecure rights look like in order to achieve economically efficient resource use or desired stewardship objectives?

While insecure rights are perhaps the most common institutional paradigm globally, the exploitation incentives have not been carefully explored.² We examine analytically the harvest and stewardship incentives

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¹For example, the 2007 reauthorization of the Magnuson–Stevens Fishery Conservation and Management Act (Public Law 94-265) includes a 10 year “limited access privilege” with the possibility of renewal, revocation, or modification.

²Our specific notion of property rights insecurity is similar to *regulated open access* in Homans and Wilen [16]. Our focus is on dynamic uncertainty over property rights, while theirs is on the insufficient delineation of rights, see also Costello and Deacon [10].

Table 1
Examples of limited-tenure property rights

Concession type	Location	Species	Duration (years)
Fisheries	Philippines	Milkfish Fry	1–5
	United States	All new transferable quota fisheries	7–10
	Mexico	Abalone, Spiny Lobster and others	20
	Cambodia	Giant Catfish, others	2
Forestry	Indonesia	Dipterocarp	10–25
	Peru	Mahogany	40
	Ghana	Mahogany, Cedar and others	40
Hunting	Namibia	Antelope, Lion, Elephants, Rhino	3
	Zambia	Buffalo and Antelope	3
	Tanzania	Buffalo and Antelope	5
Grazing	New Zealand	Grazing grasses	3–33
	United States	Warm season grasses	10

in this intermediate case of property rights security. In addition to informing the design and evaluation of limited-tenure property rights institutions, our results shed new insights into real-world empirical puzzles about why some resources are overexploited while others are efficiently managed, despite identical property rights assignments. Specifically, we empirically apply the insights of our analytical model to the spiny lobster and abalone fisheries in Baja California, Mexico.

The setup and assignment of use rights is quite general and captures the essential features of many property rights regimes in the real world. Appropriators are granted fixed-duration tenure over a renewable natural resource, such as a fishery, a forest stand, a geographic hunting block, or an aquifer. This property right designation is called a *concession* and occurs in multiple contexts in nearly every country of the world for many types of resources (see Table 1 for examples). Beyond the assignment of the concession, the regulator plays no role in management of the resource—harvest decisions are made privately, without restriction, by the appropriator.³ The appropriator (she who holds the concession) can apply for renewal of the concession, provided that certain conditions are met (e.g. that good stewardship was practiced, or a renewal target level of stock was achieved). From the subjective perspective of the appropriator, renewal will be granted with some probability. Under this insecure property rights framework, we focus on the interplay between tenure length, renewal targets and probability of renewal.

Could this version of incomplete property rights induce economically efficient exploitation? Or could such contracts be designed to induce other socially desirable outcomes that would not otherwise be internal to the sole-owner's decisions? Clearly, as the tenure length of the concession grows, the incentives become aligned with those of the sole owner. But in the real world, most concessions contracts have finite duration—typically between 1 and 40 years. Is this length *ever* sufficient to achieve the first-best or other socially desirable outcome? On what does this result depend?

We find that the possibility of renewed concessions is sufficient to cause an appropriator to choose either a good stewardship infinite-time path or a poor stewardship finite-time path. The regulator can exploit this fact to design a concessions contract that induces fully efficient exploitation, which surprisingly holds even for finite tenure and insecure property rights. To induce the first-best economic outcome, concessions contracts will have to contain longer tenure periods when: (1) species grow slowly, (2) appropriators believe the probability of renewal is small, and (3) discount rates are high. If the probability of renewal is sufficiently high (though strictly less than 1), *any* tenure length is sufficient to induce the first-best outcome. Conversely, if the probability of renewal is sufficiently low (though strictly greater than 0), *no* tenure length can induce stewardship. We also find that slackening the requirements for concession renewal can, in certain cases, be used as a substitute for longer concessions periods.

³Because we focus on the role of property rights on appropriators' decisions, we abstract away from other types of externalities that may exist under sole ownership, e.g. see Clark and Munro [7] for an example.

Our theoretical model and results form the basis for an empirical investigation. We explicitly derive the general stewardship incentives under a linear economic model with logistic growth. We apply that specific solution to the spiny lobster and abalone fisheries of Baja California, Mexico which have identical users and property right assignments and find that property rights insecurity coupled with biological growth characteristics may partially explain why the abalone fishery has under-performed relative to the spiny lobster fishery.

1. Resource extraction and property rights

The question of incentives under a concessionary regime is ultimately a question regarding property rights and resource ownership. In 1960, Ronald Coase [8] noted that in the absence of transaction costs, assignment of property rights renders the form of their assignment essentially irrelevant, as interested parties can simply trade privately to achieve efficient outcomes. The seminal work of Hardin [15] on the *Tragedy of the Commons* considered an opposing situation where a resource has no property right attached to it, and concludes that overuse is the outcome when no one owns a resource. What these two works made clear was that establishment of some form of property rights was needed to prevent overexploitation under open access. Broadly speaking, the literature has focused on these polar extremes of open access versus rent-maximizing sole ownership. Yet, as Cole [9] points out, nested private ownership within a system of public ownership is typical of many natural resources.

The role of property rights and ownership institutions in determining economic incentives has been studied since at least Demsetz [11], who noted that private ownership allows individuals to realize the rewards of their investments. Extending this logic to aggregate outcomes of property rights, Besley [2] and Acemoglu and Johnson [1] have empirically studied the connection between a country's property rights and investment and have found support for the contention that secure property rights promotes investment. Our setting involves renewable resource growth and the inherent dynamic externalities therein. The decision to restrict harvest in one period to enhance future profits is fundamentally an investment decision by the appropriator and will be affected by the completeness of the property rights governing the resource.

In considering the role of natural resource property rights, fisheries in particular have long been studied. Predating Hardin's work by more than a decade, Gordon [14] recognized that a lack of ownership of fisheries would lead to rent dissipation in a static framework, while Scott [23] added that the same lack of ownership would lead to an inefficient harvest in a dynamic sense as well. Within the context of more general resource use, Chichilnisky [4] argues that insecure property rights in a country can lead to environmental overuse relative to countries with more secure property rights due to trade, and therefore establishing more secure property rights may outperform taxes and other government policy in promoting positive environmental outcomes.

The property rights system considered here, a fixed-tenure concessions regime with the possibility of renewal, is used in a variety of contexts all over the world. Yet little analysis is available to help guide its design or predict its effects. Exceptions include a few applications to forestry and grazing leases [3,19,12].⁴ While these papers deal with incomplete property rights in specific settings, we will consider the general harvest incentives provided by concessions.

2. The model

A concession of fixed duration is granted to the appropriator of a renewable natural resource. It entitles the appropriator exclusive and unrestricted access to the resource over that time period, called a concession "block". A renewal "target" is also announced at the beginning of the concession. If, at the end of the

⁴Boscolo and Vincent [3] examine a number of alternative timber policies including concessions and conclude that longer concessions in the presence of high discounting provide little incentive for loggers to adopt less-intensive harvesting techniques. McCluskey and Rauser [19] consider grazing permits and the risk of rangeland reform and find that grazers may alter their behavior in a socially optimal way if they can avoid the risk of rangeland reform, while Egan and Watts [12] argue that a lack of secure property rights in grazing leases has caused a decline in the value of grazing permits.

concession block, the target is met, the appropriator believes the concession will be renewed with some probability which summarizes the subjective beliefs of the appropriator and is based on the history of renewal, knowledge of the regulator, etc. If the target is not met, the concession will expire at the end of the concession block.

Let X_t be the resource stock at the beginning of period t , H_t be the resource extracted that period, and $Y_t \equiv X_t - H_t$ be the population of the resource that escapes harvest for which we will adopt the term “escapement”. The escaped stock will then grow according to the biological growth function. The regulator announces to the appropriator the concession length, $\tau \geq 1$, and the renewal target \bar{S} , expressed as units of escapement at the end of the concession block.⁵ If the escapement at the end of τ periods meets or exceeds \bar{S} , then the concession is renewed, again for τ periods, with probability θ .⁶ Otherwise, the concession terminates at time τ . The regulator’s announced escapement target, \bar{S} , could reflect many social concerns. If resource yield is the only consideration, then \bar{S} is likely to be the steady-state escapement from the sole-owner’s solution under complete property rights, though other competing criteria such as ecotourism or biodiversity may influence the target.

Under this setup, from the perspective of periods $t \leq \tau$, renewal at time τ is then a Bernoulli random variable with the following probability:

$$\Pr\{\text{Renewal}\} = \begin{cases} 0 & \text{if } Y_\tau < \bar{S}, \\ \theta & \text{if } Y_\tau \geq \bar{S}, \end{cases} \tag{1}$$

where Y_τ is the escapement of the resource at the end of the first concession block.

The current period net return to the appropriator from harvesting H_t when the stock is X_t is $\pi_t(H_t, X_t)$, which we assume is continuous. The appropriator chooses a harvest path $\{H_t\}$ for $t = 1, 2, \dots, \infty$ to maximize the expected present value payoff over an infinite number of possible concession blocks (each of length τ), as follows:

$$\max_{\{H_t\}} \sum_{t=1}^{\tau} \pi(H_t, X_t) \delta^t + \sum_{i=1}^{\infty} I(Y_{i\tau}) \theta^i \sum_{t=1}^{\tau} \pi(H_{i\tau+t}, X_{i\tau+t}) \delta^{i\tau+t} \tag{2}$$

for discount factor $\delta < 1$. Eq. (2) describes the expected profit over an infinite time-horizon, where i indexes the concession block and t indexes the year within a concession block. The first term represents the profit earned over the first concession block, over which tenure is certain. It is the standard fixed terminal time resource extraction problem. The second term represents expected profit from all subsequent concession blocks. The function $I(Y_{i\tau})$ is an indicator function that indicates whether the renewal target has been met in a concession block (and in all previous concession blocks), as follows:

$$I(Y_{i\tau}) = \begin{cases} 1 & \text{if } Y_{j\tau} \geq \bar{S} \text{ for } j = 1, 2, \dots, i, \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

Uncertainty over renewal, represented here by the parameter θ , can be thought of as introducing a step-function discounting term, which is compounded every τ periods.

The optimization problem (2) is subject to the biological growth constraint: $X_{t+1} = F(Y_t) + Y_t$ for growth function $F(y)$, which has the standard properties: $F''(y) < 0$, $F(0) = F(K) = 0$ for carrying capacity, K . The other constraint is that harvest cannot exceed stock: $H_t \leq X_t, \forall t$, and the initial stock, X_1 is given. In the next section we solve the maximization problem given in Eq. (2) and extract and interpret the solution’s most salient characteristics for the design of concessions contracts.

⁵Because our model is in discrete-time, the minimum value of τ is 1.

⁶We use the step-function for clarity and mathematical simplicity. Alternatively, the assessment of renewal probability could be modeled as a smooth function of ending escapement and a signal from the regulator, $\theta(Y_\tau, \mathcal{S})$. We briefly return to this point in Section 5.

3. Results

We now derive the incentives faced by the appropriator in a concessions regime by solving and unpacking the appropriator's stochastic dynamic optimization problem given by Eq. (2). We begin with the following assumption.

Assumption 1. Optimal escapement at the end of the first tenure block (Y_τ^*) is independent of the initial starting stock (X_1).

Assumption 1 ensures that the effects of the initial stock are absent by the end of the first tenure block. Whether this holds *strictly* will depend on all features of the problem, e.g. tenure length, initial stock, form of economic model, etc.⁷ This condition is likely to hold *approximately* for a much larger class of bioeconomic models. Technically, violations of this condition change the structure of our proofs but are unlikely to appreciably change our qualitative conclusions.⁸

In our problem, learning takes a simple binary form. Updating is trivial in the sense that harvest is conditional upon renewal in all previous tenure blocks; in the event of non-renewal, future harvests are moot. This property implies that at the start of the program the appropriator can determine her entire optimal sequence of harvests over the infinite horizon, all conditional upon having been renewed in each previous tenure block.

To solve Eq. (2), we begin by considering two possible harvest trajectories, $\{H_t^I\}$ and $\{H_t^F\}$ defined as follows:

$$\begin{aligned} \{H_t^I\} = \arg \max & \left[\sum_{t=1}^{\tau} \pi(H_t, X_t) \delta^t + \sum_{i=1}^{\infty} \theta^i \sum_{t=1}^{\tau} \pi(H_{i\tau+t}, X_{i\tau+t}) \delta^{i\tau+t} \right] \\ \text{subject to } & Y_{i\tau} \geq \bar{S} \quad \forall i, \end{aligned} \quad (4)$$

$$\{H_t^F\} = \arg \max \left[\sum_{t=1}^{\tau} \pi(H_t, X_t) \delta^t \right], \quad (5)$$

where superscript I stands for “infinite” and superscript F stands for “finite”. Eq. (4) defines the harvest path that maximizes Eq. (2) under a constraint that $Y_{i\tau} \geq \bar{S}$ for all i . Under this harvest path the appropriator is *trying* to obtain renewal in all tenure blocks, though by Eq. (1), meeting the renewal target does not guarantee renewal (provided $\theta < 1$). We denote that harvest path $\{H_t^I\}$ and the escapement at the end of each concession block i of that infinite harvest path $Y_{i\tau}^I$. The associated present value profit of that harvest path is denoted $J^I(\tau, \theta, \bar{S})$.

One consequence of Assumption 1 is that this infinite harvest path profit $J^I(\tau, \theta, \bar{S})$ can be separated into two terms that delineate certain profits against uncertain future profits, as follows:

$$J^I(\tau, \theta, \bar{S}) = J_0^I(\tau, \theta, \bar{S}) + \sum_{i=1}^{\infty} J_{SS}^I(\tau, \theta, \bar{S}) \theta^i \delta^{i\tau} = J_0^I(\tau, \theta, \bar{S}) + J_{SS}^I(\tau, \theta, \bar{S}) \left(\frac{\theta \delta^\tau}{1 - \theta \delta^\tau} \right). \quad (6)$$

The associated present value profit has two components: the first component, $J_0^I(\tau, \theta, \bar{S})$, is the profit in the initial concession block, and the second component, $J_{SS}^I(\tau, \theta, \bar{S})$, is the steady-state stream of profit achieved in each subsequent block, conditional on renewal.

⁷For example, Assumption 1 holds strictly if profit is linear in harvest, a special case to which we will return.

⁸Suppose Assumption 1 is violated. For example in highly nonlinear economic systems with very large starting stock and short tenure length, it may take several tenure blocks for the effects of the starting stock to be dampened. In such cases, our analysis still applies approximately, but does not apply strictly until these effects die out. The other possible case is when starting stock is low and the species grows very slowly (relative to the tenure length). In this case the problem becomes trivial because even in the absence of harvest, achieving the renewal target is not possible. In such cases, the regulator would prohibit extraction until the stock was sufficiently rebuilt and then issue the concession. In either case the closer the stock gets to the long run steady state the more likely Assumption 1 is to hold strictly and thus the insights from this analysis become increasingly relevant.

The second harvest path that we initially consider (Eq. (5)) is that of an appropriator who does not seek renewal. We denote that harvest path $\{H_t^F\}$, the escapement at the end of the first concession block Y_τ^F and the associated maximized present value of profit over that period $J^F(\tau, \theta, \bar{S})$.

Of all possible harvest paths that could solve Eq. (2), the solution to the appropriator's problem can be narrowed down to two possibilities, $\{H_t^I\}$ or $\{H_t^F\}$, a result we formalize below. All proofs are provided in Appendix A.

Lemma 1. *Under Assumption 1 the solution to the maximization problem Eq. (2) is either the infinite path $\{H_t^I\}$ or the finite path $\{H_t^F\}$, as defined in Eqs. (4) and (5).*

The proof for this result exploits the fact that if the ending escapement in the first concession block is insufficient to meet the renewal target, ($Y_\tau < \bar{S}$), then the escapement may as well be chosen to optimize profits over the single-tenure-block time horizon. An immediate consequence of Lemma 1 is that if it is ever optimal to exhaust (or mine) the resource, it is optimal to do so in the initial tenure block.

Now that we have established these two paths as the only rational harvest paths, we interpret what these paths represent in ecological management terms. The infinite harvest path $\{H_t^I\}$ corresponds to *stewardship* of the resource in the sense that the appropriator is meeting or exceeding the renewal target set forth by the resource manager. We thus use the terms *infinite path* and *stewardship path* interchangeably. The other possibility is the finite harvest path $\{H_t^F\}$ which corresponds to a *mining* of the resource over a finite horizon, so we will use the terms *finite path* and *mining path* interchangeably. We are ultimately interested in the characteristics of a concessions contract that will lead the appropriator to choose the infinite (stewardship) path or the finite (mining) path.

A useful consequence of Lemma 1 is that, when considering tenure lengths required to induce economically efficient resource extraction, the regulator need only worry about offering enough incentive to the appropriator to make him willing to trade-off large certain short term gains in exchange for a stream of less certain long-run benefits.

3.1. Inducing stewardship

Here we compare the incentives of a concessions holder to those of the sole owner. We show the contract can be designed to induce a harvest trajectory identical to the sole owner's, formalized as follows.

Proposition 1. *Under Assumption 1, it is possible to induce first best economically efficient harvest under a limited tenure ($\tau < \infty$) and insecure ($\theta < 1$) property right.*

This striking result suggests that even with incomplete property rights, the first best harvest path can be achieved.⁹ Formally, if Y_τ^{SO} and $\{H_t^{SO}\}$ are the sole-owner's ending escapement and harvest path, then the proof shows that setting $\bar{S} = Y_\tau^{SO}$ will cause an appropriator trying to meet the renewal target to choose a harvest path identical to the sole owner's, $\{H_t^I\} = \{H_t^{SO}\}$. Furthermore, if the resulting profits from choosing $\{H_t^I\}$ exceed the short term profits from choosing $\{H_t^F\}$, then the optimal harvest path for the appropriator is identical to the economically efficient harvest path of a sole owner.

However, the proof reveals that the renewal target \bar{S} must be set equal to the sole-owner's optimal escapement Y_τ^{SO} in order for the infinite harvest path match the first best (i.e. economically efficient) harvest path. If the renewal target is instead set above the sole-owner's escapement, $\bar{S} > Y_\tau^{SO}$, for any renewal probability θ it is impossible for the infinite harvest path $\{H_t^I\}$ to equal the sole-owner's harvest path $\{H_t^{SO}\}$. If the renewal target is set below the sole-owner's escapement $\bar{S} < Y_\tau^{SO}$, then if the appropriator believes with certainty the concession will be renewed, $\theta = 1$, the infinite harvest path will again be identical to the sole owner's and therefore economically efficient. However, if the appropriator is less than certain about renewal, $\theta < 1$, the appropriator will choose to deviate from the sole-owner's path by harvesting more. In that case, because the appropriator can harvest more than the steady-state sole-owner's escapement and still obtain

⁹Later, in Proposition 4, we further strengthen this result by showing that for any θ above some threshold (though smaller than 1), the concessions contract can *always* be designed to achieve first best harvest.

renewal, the appropriator will weigh the certain extra benefit of harvesting in the current concession block against the cost of letting the stock regrow to the optimal steady state in the less certain future.

While complete property rights are sufficient for economically efficient harvest, Proposition 1 shows that they are not necessary. From the perspective of the regulator, the practical advantage of this is clear: Appropriators will behave identically to a sole owner with complete tenure, without the need to relinquish complete control of the resource in perpetuity. This analysis is useful for identifying the parameters of a contract (combinations of tenure length, renewal targets, and subjective probability renewal) that induce the stewardship path.

More generally, what is the role of the renewal target on stewardship incentives? Intuitively, \bar{S} can be thought of as how much “slack” the renewal target gives the appropriator. From the appropriator’s point of view, the question is whether to forego some current profit to leave an escapement $Y_{it} \geq \bar{S}$, thereby enjoying some possibility of concession renewal. Meeting this (optional) constraint is more costly for larger \bar{S} . Consider the trivial case where $\bar{S} = 0$. In that case, concession renewal is independent of resource use by the appropriator. While the appropriator’s exploitation incentives will depend on the probability of renewal θ , profit from the infinite harvest path always meets or exceeds that of the finite harvest path. For sufficiently large \bar{S} , the incentive to pursue renewal is always outweighed by the potential for current profits. It seems intuitive that somewhere in the middle enough slack is introduced to induce resource stewardship. We show that an interior value of \bar{S} always exists such that the appropriator would prefer an ending escapement of \bar{S} (with the associate possibility of concession renewal) to the finite path ending escapement of Y_{τ}^F . This result is formalized below.

Proposition 2. *Under Assumption 1 there always exists a renewal target $\bar{S} > Y_{\tau}^F$ that induces the stewardship path.*

Let \bar{S}^A be some particular value of the renewal target \bar{S} . If stewardship incentives are insufficient (so $J^F(\tau, \theta, \bar{S}^A) > J^I(\tau, \theta, \bar{S}^A) > 0$) then the proof shows that there will always exist a less strict renewal target \bar{S}^B with $\bar{S}^A > \bar{S}^B > Y_{\tau}^F$ that can induce stewardship $J^F(\tau, \theta, \bar{S}^B) < J^I(\tau, \theta, \bar{S}^B)$. The proof of this result uses a well-known result from resource economics that the shadow value of terminal stock in an unconstrained finite horizon problem is 0. The practical importance of this finding is that managers could use this instrument (a slack target) to “nudge” the appropriator to back off of harvest to provide a buffer against extinction or achieve other conservation goals that would not otherwise be internalized by the finite horizon appropriator.

Conversely, requiring a “too strict” renewal target (for example, requiring an escapement far above the sole-owner optimum to achieve conservation goals) can lead the appropriator to mine the resource; made formal by the following:

Corollary 1. *Under Assumption 1 and if \bar{S} is binding, if the appropriator is initially indifferent between the finite and infinite paths ($J^F(\tau, \theta, \bar{S}) = J^I(\tau, \theta, \bar{S})$), increasing \bar{S} causes the appropriator to choose the mining path $\{H_{\tau}^F\}$.*

Because the infinite harvest path represents a constrained optimization, the shadow value of the constraint \bar{S} is non-zero, thus increasing \bar{S} will decrease the profit of the stewardship path, while leaving the mining path profits unchanged. Therefore, the unintended consequence of setting a high renewal target can be that the appropriator chooses to mine the resource in the first concession period.

As we are primarily interested in economic efficiency, we will henceforth consider the renewal target \bar{S} that is equal to the level of escapement that the sole owner would choose.

Assumption 2. The renewal target \bar{S} is set equal to the sole-owner’s optimal steady-state escapement level Y_{τ}^{SO} .

We require the following technical condition:

Assumption 3. In the absence of harvest $X_{\tau} \geq \bar{S}$.

Assumption 3 simply ensures that it is possible to meet renewal. If this assumption is violated, the problem becomes trivial.

In order to explore in more detail the incentives for stewardship under concessions, we adopt a standard economic assumption.

Assumption 4. The profit expression, $\pi(H, X)$ is linear in H .

Assumption 4 further refines (and is a sufficient condition) for Assumption 1. It is well-known that such a condition yields a most rapid approach path (MRAP) solution [17]. The MRAP that results from the linear economic model implies that the steady-state escapement to which the appropriator will harvest each period is independent of the future time horizon (except in the final period),¹⁰ and is therefore independent of the future possibility of renewal. Once the steady state for the infinite harvester is reached, per-period profit is identical across periods. We denote this steady-state profit by $\bar{\pi}$. Similarly, under a MRAP solution, the finite harvest path $\{H_t^F\}$ will also generate $\bar{\pi}$ each period, save the final period. In the final period of ownership τ , the finite appropriator will mine the resource, resulting in a final period profit $\hat{\pi}$ strictly greater than $\bar{\pi}$.

To ensure that the discount rate is sufficiently low that it is in fact optimal for the finite appropriator not to harvest the entire stock in the initial period, we require that she be willing to wait at least one period before harvesting the entire stock: $\hat{\pi} < \bar{\pi} + \delta\hat{\pi}$.¹¹ Rewritten, the assumption is:

Assumption 5.

$$(1 - \delta) < \frac{\bar{\pi}}{\hat{\pi}}.$$

If Assumption 5 fails to hold, our model is still valid, but the results become trivial because the appropriator would harvest to extinction in the first period and obviously would not be renewed.

Here we expand the profit $J^F(\tau, \theta, \bar{S})$ and $J^I(\tau, \theta, \bar{S})$ that result under Assumptions 2–5. The present value of profit under the finite harvest path contains three terms. First, there are some transition profits during the MRAP (let this duration be denoted α); we denote these profits π_{MRAP}^F . Second, there are $\tau - \alpha - 1$ periods of steady-state profits ($\bar{\pi}$). Finally the profits in the final concession period are $\hat{\pi}$, as follows:

$$J^F(\tau, \theta, \bar{S}) = \pi_{\text{MRAP}}^F + \sum_{t=\alpha+1}^{\tau-1} \delta^t \bar{\pi} + \delta^\tau \hat{\pi} = \pi_{\text{MRAP}}^F + \bar{\pi} \frac{\delta^\tau - \delta^{\alpha+1}}{\delta - 1} + \delta^\tau \hat{\pi}. \tag{7}$$

Present value profit from the infinite harvest path is similarly given as follows:

$$J^I(\tau, \theta, \bar{S}) = \left(\pi_{\text{MRAP}}^I + \sum_{t=\alpha+1}^{\tau} \delta^t \bar{\pi} \right) + \sum_{i=1}^{\infty} \theta^i \sum_{t=1}^{\tau} \delta^{i+t} \bar{\pi} = \pi_{\text{MRAP}}^I + \bar{\pi} \frac{\delta^{\tau+1} - \delta^{\alpha+1}}{\delta - 1} + \bar{\pi} \frac{\theta(\delta^{2\tau+1} - \delta^{\tau+1})}{(\delta - 1)(1 - \theta\delta^\tau)}. \tag{8}$$

We do not require any assumptions regarding the initial stock beyond what is already implied by Assumption 3. Because the appropriator will take an identical MRAP to the steady-state escapement for both $\{H_t^F\}$ and $\{H_t^I\}$, the transition profits are identical: $\pi_{\text{MRAP}}^F = \pi_{\text{MRAP}}^I$. Thus, when comparing $J^F(\tau, \theta, \bar{S})$ against $J^I(\tau, \theta, \bar{S})$, any periods before reaching the steady state simply drop out of any comparison of incentives.¹²

For any concession length τ and renewal probability θ , we would like to determine $J^F(\tau, \theta, \bar{S}) \leq J^I(\tau, \theta, \bar{S})$. Consider the indifference frontier between τ and θ which is defined by the set of points such that $J^F(\tau, \theta, \bar{S}) = J^I(\tau, \theta, \bar{S})$. This equality implicitly defines θ as a function of τ along this frontier. The following proposition derives the shape of that frontier.

Proposition 3. Under Assumptions 2–5, the indifference frontier between tenure length and renewal probability is downward sloping: $d\theta/d\tau < 0$.

The implications of Proposition 3 are clear. If the appropriator is nearly certain of tenure renewal (θ is large), then a relatively short tenure length will be sufficient to induce economically efficient harvest. On the other hand, if the appropriator is less certain about tenure renewal, a longer tenure will be necessary to ensure stewardship. Furthermore, this result bisects the parameter space of renewal probability θ versus tenure length

¹⁰Clark et al. [6] point out that the presence of irreversibility in the capital stock can lead to more complex harvest trajectories, which calls into question the optimality of the MRAP. We abstract from problems of this nature, as our focus here is on the role of property rights in determining harvest incentives.

¹¹This assumption echoes the well-known result from Clark [5] that a low relative growth rate can lead a harvester to rationally extinguish a stock in the first period.

¹²We return to this result in the following section on resource characteristics.

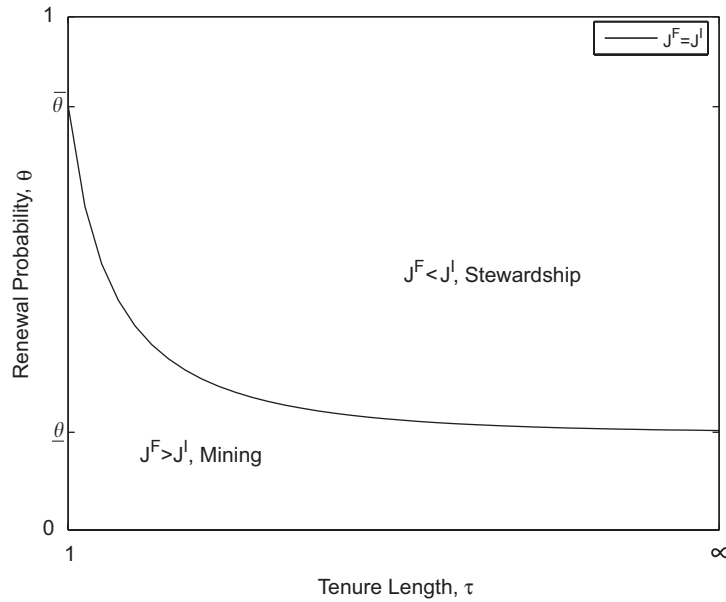


Fig. 1. Indifference frontier in (τ, θ) space between the stewardship and mining harvest paths.

τ . If we start at a point $(\tilde{\tau}, \tilde{\theta})$ of equality $J^F(\tilde{\tau}, \tilde{\theta}, \bar{S}) = J^I(\tilde{\tau}, \tilde{\theta}, \bar{S})$, then by Proposition 3 increasing either renewal probability or tenure length will lead to the infinite path being preferred, and vice versa.

Now that we have shown that the indifference frontier between θ and τ is downward sloping, we will examine existence.

Proposition 4. *Under Assumptions 2–5, there exists an upper bound on renewal probability $0 < \bar{\theta} < 1$ such that for all $\theta \geq \bar{\theta}$, the infinite path $\{H_t^I\}$ is optimal for any tenure length τ . There also exists a lower bound on renewal probability $0 < \underline{\theta} < \bar{\theta}$ such that for all $\theta \leq \underline{\theta}$, the finite path $\{H_t^F\}$ is optimal for any tenure length τ .*

From Propositions 3 and 4, we see that for $\theta > \bar{\theta}$, any tenure length will lead to the infinite harvest path, while for $\theta < \underline{\theta} > 0$, there is no tenure length that can induce stewardship, and these two bounds are connected by a downward sloping indifference frontier.

While there does not exist a τ for every θ , we will show that there is a θ for every τ .

Corollary 2. *Under Assumptions 2–5 there exists a renewal probability θ for any tenure length τ such that the finite and infinite paths yield equivalent payouts.*

Fig. 1 graphically depicts Propositions 3 and 4 and Corollary 2 by plotting the appropriator’s indifference frontier in (τ, θ) parameter space. The bold line represents the implicit indifference function such that $J^F(\tau, \theta, \bar{S}) = J^I(\tau, \theta, \bar{S})$, consistent with Proposition 3. By Proposition 4, above $\bar{\theta}$ any tenure length will induce stewardship. Below $\underline{\theta}$ no tenure length will induce stewardship. Areas above and to the right of the curve represent pairs of renewal probabilities and tenure lengths where the appropriator prefers the infinite harvest path, and points below and to the left are where the appropriate prefers the finite path. The relationship between renewal probability and tenure length is further discussed in Section 4 for a numerical example in a Baja California, Mexico fishery.

3.2. Stewardship and resource characteristics

We now consider how stewardship incentives are affected by initial abundance and growth characteristics of the resource. Would the tenure length required to induce stewardship change if the population in question was already over-exploited and in need of recovery? Intuitively, it might seem that a degraded stock might offer no short-term benefits to depletion, and therefore an appropriator would be more inclined to choose the infinite

harvest path. On the other hand, for a heavily depleted stock, the growth of the resource may be so slow as to delay any gains from harvest into the far discounted future. It turns out that for the model considered here, stewardship incentives are insensitive to initial stocks.¹³

Proposition 5. *Under Assumptions 2–5 a change in initial stock X_1 has no effect on stewardship incentives.*

Under the linear economic system considered here, the regulator need not consider the initial state of the resource when calculating the stewardship incentives for the appropriator. If the resource is significantly degraded, both the finite and infinite harvest paths will initially refrain from harvest and let the stock regrow to the (same) steady-state level. On the other hand, a virgin resource will be exploited down to the steady-state escapement in exactly the same fashion by both finite and infinite harvest paths.

We now consider the impact that the productivity of the resource has on stewardship incentives. Will increased productivity make short-run finite path gains more lucrative, or will the long-run infinite path become more attractive? Consider the following general way to incorporate productivity into this model:

$$F(Y_t) = zG(Y_t). \quad (9)$$

Here, the scalar, z serves as a multiplicative productivity parameter (where $z = 1$ implies no change from the previous analysis) and $G(Y_t)$ is a concave growth function.¹⁴ We find that more productive resources tend to favor stewardship, as is formalized by the following proposition.

Proposition 6. *Under Assumptions 2–5, if the appropriator is indifferent between the finite and infinite paths such that $J^F(\tau, \theta, \bar{S}; z) = J^I(\tau, \theta, \bar{S}; z)$, an increase in productivity z leads the appropriator to choose the infinite stewardship path $\{H_t^I\}$.*

The implication of this result is that for slow growing stocks, either a longer tenure length or more certain renewal probability will be required to prevent mining of the resource. For different species managed under similar concessions regimes, the fact that stewardship is dependent on resource productivity can have profound consequences, as seen in the illustrative example in the following section.

4. An illustration with logistic growth

Here we derive the harvest incentives under logistic growth and apply those insights to a real-world case in which concessions are used to manage two commercially important fisheries in the remote Vizcaino region of Baja California, Mexico. In this region a limited tenure concessions system as been in place since 1936. Twenty year concessions are granted to specific areas of ocean to each of a total of 26 fishing community cooperatives. The size of a typical cooperative in this region is 100 members who use around 20 boats to harvest a collection of species allowed by the federal management authority [22]. The species of greatest economic relevance are the spiny lobster (*Panulirus interruptus*) and abalone (*Haliotis*) both of which are covered under the 20 year concessions described above. These concessions for lobster and abalone have yielded mixed success.

By all indications (harvest, catch per unit effort, and stock assessments) spiny lobster has been a management success under the concessions regime. Yields are consistently high and a scientifically rigorous process of certification was successfully completed in 2004 in accordance with Marine Stewardship Council guidelines [22]. The success of the lobster fishery under concessions is in stark contrast to that of the abalone where legal yields have systematically dropped over time. Yet both of these important fisheries are regulated under identical 20 year concessions contracts. Can our theory help explain the disparity in success?

¹³Alternatively, Proposition 5 can be proven by adopting only Assumption 1. Under Assumption 1 Y_t is independent of X_1 and thus initial stock cannot affect whether the appropriator pursues the mining or stewardship path.

¹⁴A technical property that is sufficient (though not necessary) for proving Proposition 6 is $G'''(Y_t) \leq 0$. This holds, e.g., for logistic growth functions.

4.1. Incentives under logistic growth

We first abstract from the specifics and examine appropriator incentives under logistic growth of a general biological resource. We explicitly derive the indifference frontier introduced in Section 3. Under logistic growth, biomass evolves as follows: $F(Y_t) = rY_t(1 - Y_t/K)$, which we can solve for the steady-state escapement. In this model, the parameter r denotes the intrinsic growth rate of the biological population and K denotes the carrying capacity of the biological population. These parameters will differ across species, and these differences will lead to different harvest incentives of a concessions-regulated resource.

Adopting Assumptions 2–5, which nicely match the standard bioeconomics fishery problem, we can immediately write down a necessary and sufficient condition for an optimal harvest rate,¹⁵ as follows:

$$\frac{(1 - \delta)}{\delta} = F'(Y_t) = r \left(1 - 2\frac{Y}{K}\right). \quad (10)$$

Rearranging and solving for Y_t we can determine the optimal steady-state escapement, Y^* , as follows:

$$Y^* = \frac{K}{2r} \left(1 + r - \frac{1}{\delta}\right). \quad (11)$$

Finally, to find the curve of indifference between the finite and infinite harvest paths, we adopt Assumptions 2–5, set the profits equal (so $J^F(\tau, \theta, \bar{S}; z) = J^I(\tau, \theta, \bar{S}; z)$), and solve for θ . Coupling this algebraic manipulation of appropriator incentives with the logistic growth function yields an explicit expression for the indifference frontier in terms of biological, economic, and tenure contract parameters, as follows:

Proposition 7. *Under Assumptions 2–5 and with logistic growth, the indifference frontier and upper and lower bounds on θ are explicitly given as follows:*

$$\theta = \frac{2(\delta - 1)}{(\delta - 1 - r\delta) + \delta^\tau(\delta - 1 + r\delta)}, \quad (12)$$

$$\underline{\theta} = \frac{2(\delta - 1)}{\delta - 1 - r\delta}, \quad (13)$$

$$\bar{\theta} = \frac{2}{\delta + r\delta + 1}. \quad (14)$$

Because the carrying capacity drops out of the renewal probability expression, we need only estimates of the intrinsic growth parameter, r , in order to apply Eqs. (12)–(14) to abalone and spiny lobster.

4.2. Spiny lobster and Abalone in Baja California, Mexico

The spiny lobster is a relatively rapidly growing species, with an annual intrinsic growth rate of biomass of $r \approx 0.34$ (e.g. see FAO [13]), while the abalone is notoriously slow growing with an annual intrinsic growth rate of biomass of $r \approx 0.06$.¹⁶ Inserting these into Eq. (12), we can calculate the minimum renewal probability θ required to induce stewardship for any given tenure length τ and discount factor δ . These are graphed in Fig. 2 for discount factors 1.00, 0.97 and 0.95 (corresponding to discount rates of about 0%, 3% and 5%, respectively).

In all cases, the frontier is downward sloping (Proposition 3), and the upper and lower bounds on θ can be visually observed from the figures (Propositions 4 and 7). For (τ, θ) combinations above the plotted frontier, the infinite harvest path is preferred, and for combinations below the frontier, the finite harvest path is preferred. Consider, for example $\delta = 0.97$ (about a 3% discount rate). In that case, the infinite stewardship harvest path will be pursued for *any* tenure length, provided the probability of renewal exceeds 87% for

¹⁵Harvest is such that the discount rate is equal to $F'(Y_t)$.

¹⁶Authors' calculation based on estimates in [20,21,18].

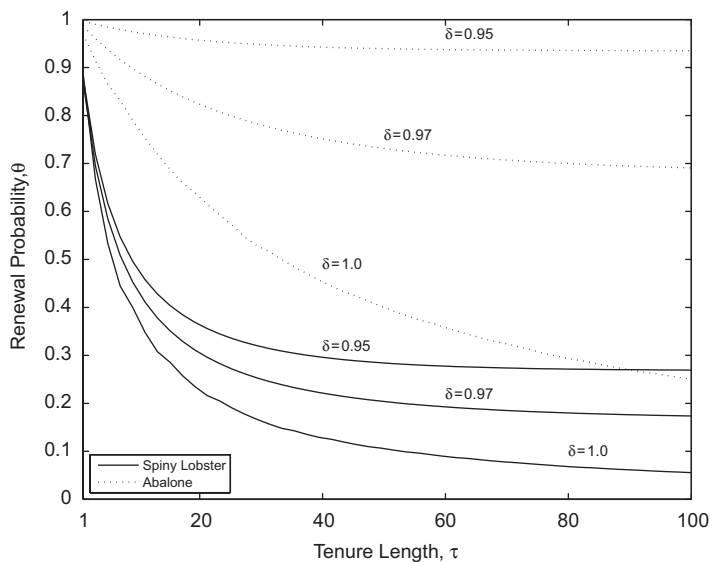


Fig. 2. Minimum renewal probability, as a function of tenure length to achieve resource stewardship. Graphs are for spiny lobster (solid) and abalone (dotted) with a discount factor of $\delta = 1.0, 0.97,$ and 0.95 .

lobster or 99% for abalone (see Eq. (12)). Conversely, no tenure length will induce the infinite path if the probability of renewal is lower than 17% for lobster or 68% for abalone.

Assuming a discount factor of $\delta = 0.97$, how likely must renewal be in order to induce the stewardship path with a 20 year concession? The lobster fishery would require only a 31% chance of renewal, while the abalone would require a significantly higher 82% chance of renewal. Higher discount rates (lower discount factors) make these values even more extreme. For $\delta = 0.95$, the abalone fishery would require nearly certain renewal (96%) to pursue the stewardship path. In all cases, lobster requires far less certainty to induce the infinite harvest path.

The implications for fishery management are quite clear from this example and are loosely consistent with observations about the performance of these two fisheries under concessions. Results suggest that for lobster management, a concessionary regime of property rights likely will lead to stewardship. On the other hand, the abalone's very slow growth rate may lead to over-harvest under concessions, especially under high discount rates. This result is in the same vein as Clark [5], in the sense that harvesting a species with slow intrinsic growth to extinction may be optimal. Here, the discount rate of the appropriator is less than the intrinsic growth rate; however the presence of the additional discounting due to uncertain concession renewal leads appropriators to mine the resource at the end of the first concession block.

5. Conclusions

We have shown that uncertainty about renewal can cause the appropriator in a concessionary arrangement to deviate from the sole-owner infinite harvest path solution and choose a short-run harvest path under which the resource is mined. Nonetheless, there will always exist a renewal target that can induce stewardship—even a first best harvest trajectory. Furthermore, there exists a minimum length of tenure that is required to induce the infinite path, and this minimum tenure is a decreasing function of the renewal probability and growth rate. Finally, we have shown a very practical result: the tenure length granted to slow growing species such as abalone may be insufficient to induce good stewardship, which may account for the poor performance of concessionary regimes for abalone as opposed to the faster growing spiny lobster.

Several observations bear further discussion. First, one could model renewal probability as a smooth function of escapement and a renewal signal (i.e. a shift parameter) from the regulator $\theta(Y_\tau, \mathcal{S})$.¹⁷ Thus, appropriators may choose more or less intensive harvest paths in response to the marginal changes in renewal probabilities. We conjecture that the more flexible function form would change the quantitative results of our analysis, but as long as the regulator is able to smoothly influence appropriator beliefs regarding renewal (through choice of \mathcal{S}), this generalization would, at least under some restrictions about the function $\theta(Y, \mathcal{S})$, not alter our qualitative conclusions. Second, to focus our analysis on the role of property rights, we have assumed away other externalities that a sole owner or concession holder may face. One possible concern is that the sole-owner's discount rate diverges from the social discount rate, and the sole-owner solution is no longer economically efficient. Clark and Munro [7] consider this case and argue that a tax on harvest could be used to align the incentives of a sole owner with the social optimum in the presence of a stock effect. It is conceivable that a tax instrument could be similarly designed to align the incentives of a concession holder to achieve first-best harvest. Finally, we have not explicitly included monitoring and enforcement, which may prove important for concessions-regulated resources. It seems plausible that endogenous enforcement activity would be strengthened by parameters that induce stewardship, particularly when monitoring involves capital expenditures.

Several additional extensions remain. For example, stochastic growth of the resource may influence the harvest paths chosen by appropriators. Risk-averse appropriators seeking renewal may choose a less-intensive harvest path to guard against the risk of a large negative environmental shock to resource stock that could jeopardize continued ownership of the resource. While the focus in this paper is on the incentives of appropriators, the incentives of regulators in offering concessions may also be a critical issue. If privatization solves the open access problem, why do we see regulators offering more limited property rights in the form of concessions? Political constraints, uncertainty over natural resources, and a concern for option values of bioeconomics systems may all play a role in shaping the incentives of regulators to offer limited property right concessions. Next steps in this vein could include combining the appropriator's incentives with the regulator's objective to design efficient incomplete property rights regimes.

The conclusions drawn from this analysis can inform institutional design at the interface of public and private ownership. Our results reveal that limited tenure contracts with the possibility of renewal can be structured to induce economically desirable, even fully efficient, extractive behavior. On the other hand, our results also show that limited tenure contracts must be secure enough to provide sufficient incentive for an appropriator to not mine the resource. Our analysis allows us to identify a tipping point in the design of successful concessions contracts that falls between the completely insecure world of open access and the completely secure world of complete property rights. While this paper focuses on the details of such contracts, the robustness of our results suggests that control over resources currently held in the public trust need not be entirely relinquished in the interest of economically efficient resource use. Rather, through careful design and attention to private economic incentives, sufficient property right security can be granted to induce socially desirable outcomes.

Acknowledgments

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Appendix A

Proof of Lemma 1. We begin by establishing that, by Assumption 1, $Y_{it} = Y_\tau$. Conditional upon renewal in the first tenure block, the infinite horizon optimization problem starting in period $\tau + 1$ is identical to the optimization problem starting in period 1, though the initial stocks may differ ($X_{\tau+1} = F(Y_\tau)$ vs. X_1). Then,

¹⁷Without the shift parameter, it would only be coincidental that this more general functional form could yield economically efficient harvest behavior. Note that in our model, the renewal target \bar{S} serves as a simple signal.

by Assumption 1, optimal escapement in period 2τ must also be Y_τ . This same logic holds for all tenure blocks, so $Y_{it} = Y_\tau$. By definition we know that $\{H_t^I\}$ maximizes Eq. (2) when $Y_{it} \geq \bar{S}$, $\forall i$. Thus if $Y_\tau \geq \bar{S}$ then the harvest trajectory must be $\{H_t^I\}$. The other possibility is that $Y_\tau < \bar{S}$, in which case renewal is not possible. Again by definition we know that $\{H_t^F\}$ maximizes Eq. (2) when $Y_\tau < \bar{S}$. Therefore the only possible harvest paths that can maximize Eq. (2) are $\{H_t^I\}$ and $\{H_t^F\}$. \square

Proof of Proposition 1. Let $\{H_t^{SO}\}$ be the optimal harvest path chosen by a sole owner for all times $t = 1, 2, \dots$, let Y_{it}^{SO} be the resulting escapement at the end of concession block i , and let J^{SO} be the sole-owner’s net present value profit over the infinite horizon. By Assumption 1 $Y_{it}^{SO} = Y_\tau^{SO} \forall i$. Suppose the renewal target \bar{S} is set equal to the sole-owner escapement Y_τ^{SO} . From Lemma 1, we need only consider $\{H_t^I\}$ and $\{H_t^F\}$ as defined in Eqs. (4) and (5). To obtain renewal in each concession block i , the appropriator must meet or exceed the renewal target \bar{S} , so $Y_{it}^I \geq \bar{S}$. But because Y_τ^{SO} is optimal for the sole owner, the infinite path appropriator could not garner any additional profit by deviating above the sole-owner’s path, so $\{H_{it}^I\} = \{H_{it}^{SO}\}$ for all concession blocks.

Can $J^I(\tau, \theta, \bar{S}) > J^F(\tau, \theta, \bar{S})$? If the appropriator has a subjective renewal probability of $\theta = 0$, then by Eq. (5) the mining path $\{H_t^F\}$ represents the optimal harvest path over τ years because it is the unconstrained finite period maximization solution, and thus $J^F(\tau, 0, \bar{S}) > J^I(\tau, 0, \bar{S})$. If $\theta = 1$, renewal is certain and the infinite harvest path is identical to the sole-owner’s harvest path $\{H_{it}^I\} = \{H_{it}^{SO}\}$, so the infinite harvest profit is identical to the sole-owner’s profit $J^I(\tau, 1, \bar{S}) = J^{SO}$. Thus the infinite harvest profit will strictly exceed the finite harvest path profit, $J^F(\tau, 1, \bar{S}) < J^I(\tau, 1, \bar{S})$.

Finally, provided that $J^I(\tau, \theta, \bar{S})$ is continuous in θ , then by the Intermediate Value Theorem there exists some interior value $0 < \theta < 1$ where property rights are not secure such that $J^F(\tau, \theta, \bar{S}) < J^I(\tau, \theta, \bar{S})$. That $J^I(\tau, \theta, \bar{S})$ is continuous in θ can be seen by inspecting Eq. (6) and noting that the harvest path, and therefore J_0^I and J_{SS}^I are independent of θ . The final term is continuous in θ by inspection. \square

Proof of Proposition 2. Suppose the renewal target \bar{S}^B is set to be the finite path ending escapement plus some small amount $\bar{S}^B = Y_\tau^F + \varepsilon$. By Lemma 1, the appropriator then compares the profit received under the finite path with $\Pr\{\text{Renewal}\} = 0$ (with ending escapement Y_τ^F) against the profit received under the infinite path at $Y_\tau^F + \varepsilon$ with $\Pr\{\text{Renewal}\} = \theta > 0$. At the finite harvest path terminal escapement of Y_τ^F , the marginal cost of foregoing a marginal harvest unit is exactly 0.¹⁸ But at that point the marginal benefit of foregoing an infinitesimal harvest (and thus enjoying renewal probability θ) is $J_{SS}^I(\tau, \theta, \bar{S}^B)(\theta\delta^\tau / (1 - \theta\delta^\tau))$, which is strictly positive.¹⁹ Therefore, the appropriator prefers an ending escapement of $Y_\tau^F + \varepsilon = \bar{S}^B$ to an ending escapement of Y_τ^F , and $J^I(\tau, \theta, \bar{S}^B) > J^F(\tau, \theta, \bar{S}^B)$. \square

Proof of Corollary 1. By assumption the target \bar{S} is binding so $Y_{it}^I = \bar{S}$. By Lemma 1 it is sufficient to consider only the solutions $\{H_t^I\}$ and $\{H_t^F\}$. The appropriator is indifferent between the infinite harvest path and the finite harvest path such that $J^F(\tau, \theta, \bar{S}) = J^I(\tau, \theta, \bar{S})$. The marginal cost of increasing this constraint to some other renewal target $\bar{S}^B > \bar{S}$ is strictly positive because the terminal shadow value of the stock in a (binding) constrained optimization is positive. Thus, increasing the target to \bar{S}^B decreases the infinite harvest path profit. The finite harvest path, and thus its associated profit, remains unchanged. Thus the increase in \bar{S} leads the mining path to be preferred to the stewardship path $J^F(\tau, \theta, \bar{S}^B) > J^I(\tau, \theta, \bar{S}^B)$. \square

Proof of Proposition 3. Note that Assumption 1 is implied by the adopted assumptions, and we can thus apply Lemma 1. We totally differentiate the expression $J^F(\tau, \theta, \bar{S}) - J^I(\tau, \theta, \bar{S}) = 0$ in the neighborhood of (τ_c, θ_c) where $J^F(\tau_c, \theta_c, \bar{S}) - J^I(\tau_c, \theta_c, \bar{S}) = 0$, which gives us

$$d\theta \left(\frac{\partial J^F}{\partial \theta} - \frac{\partial J^I}{\partial \theta} \right) + d\tau \left(\frac{\partial J^F}{\partial \tau} - \frac{\partial J^I}{\partial \tau} \right) = 0. \tag{15}$$

¹⁸The shadow value is equal to zero, see Theorem 17.15 in Sydsaeter et al. [24].

¹⁹The appropriator gains the discounted benefits from concession block $i = 1$ onward.

By the Implicit Function Theorem (see Theorem 4.17 in Sydsæter et al. [24]), this gives us the expression we wish to sign:

$$\frac{d\theta}{d\tau} = \frac{\left(\frac{\partial J^F}{\partial \tau} - \frac{\partial J^I}{\partial \tau}\right)}{\left(\frac{\partial J^I}{\partial \theta} - \frac{\partial J^F}{\partial \theta}\right)}. \quad (16)$$

We begin with the denominator. The finite harvest profit does not depend on the probability of renewal θ , so $\partial J^F/\partial \theta = 0$, and differentiating Eq. (8), $\partial J^I/\partial \theta > 0$, thus the denominator of Eq. (16) is positive. Next, we consider the numerator. Adopting Assumptions 2–5, we can write the finite and infinite harvest profit as in Eqs. (7) and (8). Partially differentiating the finite harvest profit (Eq. (7)) with respect to tenure length τ gives

$$\frac{\partial J^F}{\partial \tau} = (\delta^\tau \bar{\pi} + \delta^\tau \hat{\pi}(\delta - 1)) \frac{\ln(\delta)}{(\delta - 1)}, \quad (17)$$

while partially differentiating infinite harvest profit (Eq. (8)) with respect to length τ gives

$$\frac{\partial J^I}{\partial \tau} = \frac{\bar{\pi} \delta^{\tau+1} (1 - \theta) \ln(\delta)}{(1 - \delta^\tau \theta)^2 (\delta - 1)}. \quad (18)$$

Because we are along the frontier where $J^F(\tau, \theta, \bar{S}) = J^I(\tau, \theta, \bar{S})$, we set Eq. (7) equal to Eq. (8) and solve for the finite terminal profit $\hat{\pi}$ which gives

$$\hat{\pi} = \frac{\bar{\pi}(1 + \delta(\theta - 1) - \delta^\tau \theta)}{(\delta - 1)(\delta^\tau \theta - 1)}. \quad (19)$$

Plugging (19) into (17) and dividing (18) by (17) gives

$$\frac{\frac{\partial J^I}{\partial \tau}}{\frac{\partial J^F}{\partial \tau}} = \frac{1}{(1 - \delta^\tau \theta)} > 1, \quad (20)$$

and therefore, $\partial J^I/\partial \tau > (\partial J^F/\partial \tau)$. Because the denominator of Eq. (16) is positive and by Eq. (20) the sign on the numerator of Eq. (16) is negative, we conclude that $d\theta/d\tau < 0$ and the indifference frontier between tenure length and renewal probability is downward sloping. \square

Proof of Proposition 4. Note that Assumption 1 is implied by the adopted assumptions, and we can thus apply Lemma 1. First, we find the upper bound. By Proposition 3 we need only consider the shortest possible tenure length $\tau = 1$. We will find the upper bound $0 < \theta < 1$ where the finite and infinite profits are equal $J^F(1, \theta, \bar{S}) = J^I(1, \theta, \bar{S})$. Setting profits equal and solving for θ gives the critical renewal probability

$$\theta = \frac{1}{\delta} \left(1 - \frac{\bar{\pi}}{\hat{\pi}}\right). \quad (21)$$

In order for this renewal probability to be interior ($0 < \theta < 1$), it must be the case that

$$0 < \frac{1}{\delta} \left(1 - \frac{\bar{\pi}}{\hat{\pi}}\right) < 1. \quad (22)$$

Because $\hat{\pi} > \bar{\pi}$ the left-hand inequality always holds. The right-hand inequality can be rewritten as

$$(1 - \delta) < \frac{\bar{\pi}}{\hat{\pi}}, \tag{23}$$

which holds by Assumption 5.

Next, we consider the lower bound. By Proposition 3, the most favorable tenure length is $\tau \rightarrow \infty$. As tenure length τ approaches infinity, the renewal probability θ necessary to induce stewardship approaches some asymptotic value $\underline{\theta} > 0$.

Let $\delta^\tau = \varepsilon$. Setting equal the finite and infinite profit Eqs. (7) and (8), plugging in $\delta^\tau = \varepsilon$ and solving for renewal probability θ yields

$$\theta = \frac{(\hat{\pi} - \bar{\pi})(\delta - 1)}{\hat{\pi}(\delta - 1)\varepsilon + \bar{\pi}(\varepsilon - \delta)}. \tag{24}$$

As we let $\tau \rightarrow \infty$, $\varepsilon \rightarrow 0$, and (24) approaches

$$\theta \rightarrow \underline{\theta} = \frac{(\hat{\pi} - \bar{\pi})(1 - \delta)}{\bar{\pi}\delta}, \tag{25}$$

which is strictly positive when discounting is non-zero ($\delta < 1$). \square

Proof of Corollary 2. We have shown in Proposition 4 that when $\tau = 1$, \exists an upper bound on renewal probability, $0 < \bar{\theta} < 1$, such that the profits from infinite and finite harvests are equal. For $\tau > 1$, we know from Proposition 3 that $d\theta/d\tau < 0$, and again from Proposition 4 we know that as $\tau \rightarrow \infty$, $\theta \rightarrow \underline{\theta}$. Therefore, at each tenure length τ , \exists a renewal probability θ such that $J^F(\tau, \theta, \bar{S}) = J^I(\tau, \theta, \bar{S})$. \square

Proof of Proposition 5. Note that Assumption 1 is implied by the adopted assumptions, and we can thus apply Lemma 1. Because the optimal strategy for both harvest paths involves an MRAP [17], a change in initial stock affects both harvest trajectories equally. Therefore, the initial stock has no effect on stewardship incentives. \square

Proof of Proposition 6. Note that Assumption 1 is implied by the adopted assumptions, and we can thus apply Lemma 1. In steady state, harvest equals growth. Let $Y_t(z)$ be the steady-state escapement so the growth is $F(Y_t(z)) = zG(Y_t(z))$. Assumption 4 implies that the steady-state profit is proportional to this harvest and is given by $\bar{\pi} = zG(Y_t(z))$. Assumption 4 also implies that the final period profit earned by the finite harvest path, $\hat{\pi}$, is proportional to the steady-state stock. The stock harvested in the final period is simply the sum of growth at the steady-state escapement plus the steady-state escapement itself. Thus under Assumptions 2–5, the profit earned in the final period by a finite path harvester is $\hat{\pi} = zG(Y_t(z)) + Y_t(z)$.

We rearrange $J^F(\tau, \theta, \bar{S}; z) = J^I(\tau, \theta, \bar{S}; z)$ and solve for renewal probability θ :

$$\theta = \frac{(\hat{\pi} - \bar{\pi})(\delta - 1)}{\hat{\pi}(\delta - 1)\delta^\tau + \bar{\pi}(\delta^\tau - \delta)}. \tag{26}$$

Inserting $\hat{\pi}$ and $\bar{\pi}$ as defined above yields:

$$\theta = \frac{Y_t(z)(\delta - 1)}{(\delta - 1)\delta^\tau Y_t(z) + z\delta(\delta^\tau - 1)G(Y_t(z))}. \tag{27}$$

Armed with θ , we can now differentiate θ with respect to productivity z . The expression that we need to sign is

$$\frac{\partial \theta}{\partial z} = (\delta - 1)\delta(1 - \delta^\tau) \frac{\left(G(Y_t(z)) \left(Y_t(z) - z \frac{\partial Y_t}{\partial z} \right) + z Y_t(z) \frac{\partial G}{\partial Y_t} \frac{\partial Y_t}{\partial z} \right)}{\left((\delta - 1)\delta^\tau Y_t(z) + z\delta(\delta^\tau - 1)G(Y_t(z)) \right)^2}. \tag{28}$$

The product of the constants in front is negative, and the denominator is clearly positive, therefore we need to sign the numerator. To determine the sign on $\partial G/\partial Y_t$, we look at the optimal condition on harvest. Harvest is chosen such that $(1 - \delta)/\delta = zG'(Y_t)$, thus, $\partial G/\partial Y_t > 0$. In order to sign $\partial Y_t/\partial z$, we totally differentiate the optimal harvest condition to obtain $\partial Y_t/\partial z = -G'(Y_t)/zG''(Y_t)$. By the concavity of $G(Y_t)$, $\partial Y_t/\partial z > 0$.

Finally, as long as $Y_t(z)$ is concave with respect to z , the term $(Y_t(z) - z(\partial Y_t/\partial z))$ is positive. We differentiate $\partial Y_t/\partial z$ derived above with respect to z to obtain the second derivative:

$$\frac{\partial^2 Y_t}{\partial z^2} = \frac{-zY_t'(z)G''(Y_t(z))^2 + G'(Y_t(z))(G''(Y_t(z)) + zY_t'(z)G'''(Y_t(z)))}{z^2G''(Y_t(z))^2}. \quad (29)$$

The denominator is clearly positive, and by our assumption in Footnote 14 and our results above, the numerator is negative, thus $\partial^2 Y_t/\partial z^2 < 0$ and Y_t is concave in z . Therefore the numerator of (28) is unambiguously positive. Thus, $\partial\theta/\partial z < 0$. Because an increase in productivity requires smaller renewal probability to make the appropriator indifferent, we have $J^I(\tau, \theta, \bar{S}; z') > J^F(\tau, \theta, \bar{S}; z')$, for $z' > z$, and the infinite path is chosen. \square

Proof of Proposition 7. The assumptions for Proposition 7 match those of Proposition 6, thus we can utilize the methodology employed in the proof of Proposition 6. Rewriting Eq. (27) using $F(Y_t(z)) = zG(Y_t(z))$ gives

$$\theta = \frac{Y_t(z)(\delta - 1)}{(\delta - 1)\delta^\tau Y_t(z) + \delta(\delta^\tau - 1)F(Y_t(z))}. \quad (30)$$

Logistic growth $F(Y_t) = rY_t(1 - (Y_t/K))$ yields steady-state escapement $Y^* = (K/2r)(1 + r - (1/\delta))$. Inserting Y^* in for $Y_t(z)$ and the logistic growth function into Eq. (30) yields the explicit Eq. (12). Letting $\tau \rightarrow \infty$ in Eq. (12) yields $\underline{\theta}$, and setting $\tau = 1$ gives $\bar{\theta}$. \square

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