Limited tenure concessions for collective goods

Nicolas Quérou, Agnes Tomini, Christopher Costello

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Nicolas Quérou[†], Agnes Tomini[‡], and Christopher Costello[§]

Abstract

Under what conditions can limited-tenure concessions be used to efficiently govern natural resources and other public goods? We first show in a simple repeated game setting that limited tenure, with the possibility of renewal, can incentivize socially-efficient provision of public goods. We then analyze the ability of this instrument to incentivize the first best for common-pool natural resources such as fish and water, thus accounting for spatial connectivity and natural growth dynamics of the resource. The duration of tenure and the dispersal of the resource play pivotal roles in whether this limited-duration concession achieves the socially optimal outcome. Finally, in a setting with costly monitoring, we discuss the features of a concession contract that ensure first-best behavior, but at least cost to the implementing agency.

Key words: Concessions, public goods, cooperation, natural resources, spatial externalities, dynamic games

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1 Introduction

The provision of impure public goods has received sustained attention because of its empirical relevance across a wide range of settings (see Samuelson (1954), Buchanan

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[†]Corresponding author; CEE-M, Univ. Montpellier, CNRS, INRA, SupAgro Montpellier, Montpellier, France. E-mail: nicolas.querou@supagro.fr

[‡]Aix-Marseille University, CNRS, EHESS, Centrale Marseille, AMSE, 5-9 Bd Maurice bourdet, F-13001, Marseille, France. E-mail: agnes.tomini@univ-amu.fr

[§]Bren School, UCSB and NBER, Santa Barbara CA, 93106, USA. E-mail: costello@bren.ucsb.edu

(1965), Berglas (1976), or Cornes and Sandler (1996)). Public goods and common-pool resources cannot, in general, rely only on voluntary contributions (Kotchen 2006; Marx and Matthews 2000), so their efficient provision remains a challenge. The incentive problems identified in the public goods literature may hinder the sustainable use of natural resources, which, across a range of applications from water to fisheries, are often overexploited (Costello et al. 2016; World Resource Institute 2019). Similar challenges arise for the use of public goods such as collective infrastructure systems, biodiversity protection, or provision of services by agricultural cooperatives.[1]

We propose an institution for governing public goods and natural resources called a *limited-tenure concession*. Versions of this institution are employed widely across the world, but little economic analysis has been undertaken to guide design. We make three contributions. First, we show in a repeated public good contribution game that limited-tenure concessions can incentivize efficient provision of public goods. Second, we extend the model to account for characteristics of common-pool resources more typical in natural resource settings: spatially-connected resources, and growth dynamics. We show that the system can incentivize the first best. Finally, in a setting with costly monitoring of a concession contract by an implementing agency, we discuss the features that ensure first-best behavior, but at least cost to implement. All results are analytically derived, allowing us to draw general conclusions.

Due to over-extraction problems, many countries have devolved the management of forests, fisheries, game, irrigation water, gas and oil to states, communities, or individuals in the form of property rights. One of the most common approaches is to assign a *concession* to a private agent. We define a concession as a limited-duration assignment of a property right, in which the temporary owner can extract natural resources during the concession period, and under some conditions, the concession may be renewed. Design features such as tenure length and renewal requirements deeply influence extraction incentives: With short tenure, and no renewal, incentives to over-extract are high, but the possibility of renewal may reverse this incentive.

This problem is closely related to the under-provision of public goods by private agents, due to free-riding.[2] In the public good setting, a concession can be similarly thought as a limited-duration assignment of a property right, in which the temporary member can contribute to and benefit from the public good during the concession period, and the concession is subject to conditional renewal. We first develop the

[1] Other relevant examples include green goods and climate protection infrastructure, provided their collective benefits may be potentially excludable. We refer to Section 2 for a discussion of other consistent real-world examples.

[2] Bergstrom et al. (1986) provides the seminal paper on this issue, which has received attention in many areas, for instance in the environmental field (Vicary 2000; Kotchen 2006; Kotchen 2009).

model in this setting where members have limited tenure. The regulator can renew tenure to any member, and agrees to do so if and only if this member has contributed a minimum level of public good in every tenure period. We show that this system can incentivize socially-efficient provision of the public good by these private actors.

Natural resources generalize this case in important dimensions: they may have resource growth, mobility, heterogeneity across space, which exacerbate the tragedy of the commons.[3] When concessions are awarded over a fixed geographical area, the resources they are meant to encapsulate may disperse beyond the concessionaire's domain; this could significantly alter incentives for efficient resource use, since this implies a spatial externality.[4] We thus amend the model to account for these characteristics. Introducing a set of spatially-distinct property right owners, we consider three management regimes: (i) the socially optimal regime, (ii) the decentralized regime and (iii) the concession regime. The last regime involves assigning limited-duration tenure of each patch to a concessionaire, with conditional renewal. The regulator announces for each patch a "minimum stock," below which the concessionaire should never extract. This is a stylized version of how many concessions are implemented.[5] Each concessionaire must decide whether to comply or to defect, given that her payoff will depend on others' strategies. Complying guarantees renewal, which raises future payoffs, while driving the stock below the requirement returns large current payoffs, but ensures the contract will not be renewed.

We show that the instrument can incentivize the first best in this setting, and analyze the properties ensuring cooperation. We find an interesting result: longer tenure is more likely to lead to defection from the first best. It has crucial implications for policy design, and it seems to contradict the intuition that more secure property rights (here, the longer the tenure duration) give rise to more efficient resource use. Indeed, Costello and Kaffine (2008) show that any tenure length may induce efficient resource use, provided the renewal probability is high enough. In our paper, under a long tenure period the regulator loses the ability to affect an agent's incentives via the promise of tenure renewal. Thus, for sufficiently long tenure length, concessionaires always defect: tenure must not be too long. Finally, we discuss how concessions may

[3]For instance, Cornes and Sandler (1983) provide a detailed analysis of this tragedy.

[4]The world's oceans consist of about 200 property right assignments (exclusive economic zones) traversed by species such as tuna, sharks, and whales (White and Costello 2014). The mismatch between the scales of property rights and of the resource is emphasized as a limitation (Aburto-Oropeza et al. 2017) for mobile resources (Costello et al. (2015) or Kapaun and Quaas (2013)).

[5]TURF systems in Japan, Mexico and Chile contain maximum harvest provisions, whose adherence is required for renewal. As a yearly stock assessment is carried out by consultants approved by the government to determine a total allowable catch (TAC) for each TURF, such a requirement may translate into a minimum stock requirement. See Hilborn et al. (2005) for related discussions.

still induce first-best behavior under costly monitoring or imperfect enforcement.

This discussion highlights the shortcomings of short tenure equal to, say, a single period. That case corresponds more closely to command and control regulation: yet, compliance is incentivized by the promise of renewal, rather than punished with a monetary penalty. Short tenure can induce efficient behavior, but would be costly to implement if more frequent monitoring brings higher costs. Thus, shorter tenure may induce stronger incentives to comply, but could increase the expected monitoring costs. We analytically solve for the tenure length ensuring compliance at least cost.

A related literature applies property rights theory to common-pool resource management. First, it analyzes the dichotomy between private (Demsetz 1967; Cheung 1970) vs. common property rights (Ostrom 1990), and instruments to implement these regimes. Two such instruments are *spatial property rights* and *use rights on the resource*. The first instrument assigns rights to extract a specified quantity of the resource; The second one designs rules of exploitation in a limited area. Spatial use rights grant secure rights to parts of a resource (Fischer and Laxminarayan 2010), as in concession systems. Our instrument can thus be used as a coordination device to overcome the externality problems caused by public goods or by common-pool resources. Second, this literature considers conditional property rights, which are allocated *ex ante* and materialize only under certain conditions (Maskin and Tirole 1999). A concession is granted conditionally on the concessionaire's pattern of resource extraction.[6] One related application is oil field unitization (Libecap and Wiggins 1985), which aims at reducing externalities from a migratory common-pool resource with important specifications (duration, economic sharing rules). Here we design a concession contract stipulating conditions defining the renewal process.

The paper is structured as follows: Section 2 introduces a motivating model of the private contribution to a public good and highlights how a concession alters incentives for private provision. In Section 3 the model is generalized to allow for heterogeneity and complex resource dynamics. In Section 4 we highlight the conditions for cooperation with an emphasis on spatial characteristics of the model and the tenure length. Section 5 provides additional results and discussions about various extensions and Section 6 concludes the paper. Proofs are provided in an Appendix.

[6]Conditional payment schemes, such as payments for ecosystem services (PES), are used to induce a specific ecological outcome. Our instrument raises similar issues about contract duration. Yet PES are based on payments: When natural resources are regulated at the national or local scale, our non-monetary instrument may be more feasible when regulators have budget restrictions.

2 A simple model of public good contributions

To motivate our main contribution, and to build intuition, we begin with a simple model of individual behavior with both private and public consequences. This is initially a static game setting in which (exogenous) N agents interact, where agent i chooses action z_i (such as resource extraction), taking as given the actions of her competitors. Let agent i's utility function in this static game be given by:

$$u_i(z_i) + v\left(\Phi - \sum_l z_l\right) \tag{1}$$

where $u_i(z_i)$ denotes the private component of agent i's utility, $v(\cdot)$ represents the public component, which depends on all agents' behaviors, and Φ is a fixed constant (for example, this could be the resource stock at the beginning of any given period). Here, greater values of z_i increase the private component of utility ($u_i'(z_i) > 0$), but confer a public cost, since the public component of agent i's utility decreases as z_i increases. Consistent with well-known results about the private (under) provision of public goods,[7] it is straightforward to show that private agent i chooses excessively high z_i. Agent i maximizes Equation 1 by setting $u_i'(\hat{z}_i) = v'(\Phi - \sum_l \hat{z}_l)$, while the social planner would like to maximize the sum of utility across all agents, so she sets $u_i'(z_i^*) = Nv'(\Phi - \sum_l z_l^*)$. Provided both $u_i(\cdot)$ and $v(\cdot)$ are increasing and concave, the under-provision of the public good is ensured, so private agents will choose excessively high action levels: $\hat{z}_i > z_i^*$.

Now consider an infinitely repeated version of this public good provision game, where N members contribute to, and enjoy the benefits from, the public good provision for a limited duration tenure. For example, tenure may extend for a period of $T = 10$ years. The regulator in this setting has the ability to renew tenure to agent i, and agrees to do so if and only if agent i has acted responsibly, that is, if and only if she has chosen z_i^* in every preceding period (up to T). This limited-duration tenure with the possibility of renewal is the focus of the rest of this paper, and in this section we use this simple setup to ask under what conditions this institution can induce efficient provision of the public good.

Clearly, the enticement of renewal induces a tension in agent i's decision about her contribution. On one hand, as was shown above, she maximizes her single-period payoff by choosing a contribution to the public good that is lower than the socially optimal level. On the other hand, the revocation rule ensures that by doing so,

[7] This public good is more aptly referred to as an *excludable public good*, because we restrict its consumption to a limited set of N agents. In this way our model departs from a pure public good setting, see Wang and Zudenkova (2016) for a recent analysis.

she will obtain zero benefit from period T onward. This tradeoff – of large current period benefits from defection vs. infinite, though lower, benefits from cooperation – is similar to the tradeoff in a Nash Reversion punishment strategy (see, e.g., Mas-Colell et al. (1995)), except that: (1) the punishment happens at date T (not immediately upon defection), (2) the punishment payoff is zero (rather than the Nash equilibrium), and (3) under this setup, other players besides i are not required to play Nash upon defection. Despite these differences, it is straightforward to show that this type of concession contract can still maintain cooperation around z_i^*, and that there is a Folk-theorem-like result that ensures cooperation (see Mailath and Samuelson (2006)).

Provided that all other agents follow the rule stipulated by the concession contract, agent i's cooperation payoff is given by:

$$\Pi_i^C = \frac{u_i(z_i^*) + v\left(\Phi - \sum_l z_l^*\right)}{1-\delta} \tag{2}$$

where δ is the discount factor. Instead, if agent i defects, she will do so in the first tenure block, so her defection payoff is:

$$\Pi^D = \frac{\left(1-\delta^{T+1}\right)}{1-\delta}\left[u_i(z_i^D) + v\left(\Phi - \sum_{l\neq i} z_l^* - z_i^D\right)\right] + 0 \tag{3}$$

which is just the defection payoff for a total of T periods and zero thereafter.[8] In this simple situation the agent compares $\Pi_i^C \lesseqgtr \Pi_i^D$. Straightforward algebraic manipulation implies that a necessary and sufficient condition ensuring that the limited-tenure instrument induces the first-best outcome as an equilibrium is the following:

$$\delta^{T+1} > \frac{u_i(z_i^D) + v(\Phi - \sum_{l\neq i} z_l^* - z_i^D) - \left(u_i(z_i^*) + v\left(\Phi - \sum_l z_l^*\right)\right)}{u_i(z_i^D) + v(\Phi - \sum_{l\neq i} z_l^* - z_i^D)} \tag{4}$$

The right hand side is the percentage loss in single-period utility to agent i from cooperating, rather than defecting. If the discount factor is sufficiently large, so agents are sufficiently patient, then cooperation will always be supported as an equilibrium outcome. Notice that, depending on the fundamentals, the actual value of the bound defined in condition 4 might not be very high. One interesting consequence of Condition 4 is that longer tenure blocks (i.e. larger T) require higher discount factors (i.e. lower discount rates) to sustain cooperation – sustaining cooperation under a long tenure period requires more patience on the part of the agents.

[8] Defection strategy z_i^D is, implicitly, $u_i'(z_i^D) = v'\left(\Phi - \sum_{l\neq i} z_l^* - z_i^D\right)$.

Even the simple repeated game presented here provides some useful and interesting insights about the ability of a limited tenure concession to induce socially optimal provision of a public good. But because our motivation is also to examine whether this kind of limited-tenure concession can help solve the tragedy of the commons for complex natural resources, the simple model here will require some elaboration. In what follows, we maintain the basic idea behind this simple model, but allow for a sophisticated array of economic and ecological interactions including spatially-owned natural resource patches, natural resource growth and dispersal across space, and strategic incentives across patch owners. While many nuances arise, our overall conclusion will be that the basic insights developed above are maintained in that richer environment.

3 Model & strategies

We now introduce a model of natural resource exploitation with spatially-connected property owners. We then home-in on the incentives for harvest strategies corresponding to three property right regimes: a social planner optimizing resource extraction over space and time; decentralized perpetual property right holders; the case of decentralized limited-tenure concessions, on which we focus. The social planner's benchmark and the case of perpetual property right holders have been analyzed previously in the literature: we briefly state the corresponding properties.

3.1 The model

We follow the basic setup of Costello et al. (2015) where a natural resource stock is distributed heterogeneously across a discrete spatial domain consisting of N patches or properties. Patches may be heterogeneous in size, shape, economic, and environmental characteristics, and resource extraction can occur in each patch. Using a discrete-time model, the stock residing in property i at the beginning of time period t is given by x_{it}, and harvests undertaken in that property, h_{it}, reduces the stock over the course of that time period: Thus leaves a "residual stock" at the end of the period of $e_{it} \equiv x_{it} - h_{it}$. The residual stock may grow, and the growth conditions may be patch-specific denoted by the parameter α_i. Finally, as the resource is mobile and can migrate around this system, we follow the natural science literature (see, e.g., Nathan et al. (2002), or Siegel et al. (2003)) who denote dispersion by $D_{ij} \geq 0$ the fraction of the resource stock in patch i that migrates to patch j in a single time period.[9] Since some fraction of the resource may indeed flow out of the system entirely, the dispersal fractions need not sum to one: $\sum_i D_{ji} \leq 1$. The equation of motion in patch i is thus given as follows:

$$x_{it+1} = \sum_{j=1}^{N} D_{ji} g(e_{jt}, \alpha_j). \tag{5}$$

Here $g(e_{jt}, \alpha_j)$ is the period-t resource growth in patch j. As usual we require that $\frac{\partial g(e,\alpha)}{\partial e} > 0$, $\frac{\partial g(e,\alpha)}{\partial \alpha} > 0$, $\frac{\partial^2 g(e,\alpha)}{\partial e^2} < 0$, and $\frac{\partial^2 g(e,\alpha)}{\partial e \partial \alpha} > 0$.[10] We also assume that extinction is absorbing, $g(0; \alpha_j) = 0$, and that the growth rate is finite, $\frac{\partial g(e,\alpha)}{\partial e}|_{e=0} < \infty$.[11] All standard biological production functions are special cases of $g(e, \alpha)$.

We assume that both price and marginal harvest cost are constant in a patch, though they can differ across patches. The resulting *net price* is given by p_i.[12] The current profit from harvesting $h_{it} \equiv x_{it} - e_{it}$ in patch i at time t is:

$$\Pi_{it} = p_i \left(x_{it} - e_{it} \right). \tag{6}$$

We will employ this framework to compare the outcome and welfare implications of three alternative property right systems. At this stage it is important to make the following observation. Real world natural resource management is more complex than the setting depicted here. For instance, there could be more complicated cost structures. We propose a relatively simple, analytically tractable model to gain insights on the performance of our concession instrument, while keeping the most relevant features when studying this issue. This model allows for dynamic and spatial externalities, and for strategic behavior between patch owners. It allows to gain sharp insights on the effects of ecological and economic fundamentals and of features

[9] When $j = i$ parameter D_{ii} denotes the fraction of the resource stock in patch i that remains in this patch. This model assumes density-independent dispersal parameters, D_{ij}. We thus follow a large part of the literature on metapopulation and source-sink dynamics (Sanchirico and Wilen 2009). This allows us to analyze the comparative statics effect of dispersal on cooperation vs. defection incentives. In Section 5.3 we consider the case of density-dependent dispersal.

[10] These assumptions must be satisfied within the relevant range of variable e. The logistic growth function is consistent with them.

[11] We will omit the growth-related parameter except briefly before Section 3.2 and in Section 3.3, where its effect will be analyzed. Thus, we will use the notation $g_i'(e)$ and $g_i''(e)$ instead of (respectively) $\frac{\partial g(e,\alpha_i)}{\partial e}$ and $\frac{\partial^2 g(e,\alpha_i)}{\partial e^2}$ in most parts of the paper.

[12] This assumption is fairly common and consistent with cases where the market price is the same in all patches, while marginal costs are patch-specific (due to geographical locations, different costs of access). Moreover, for many natural resources the number of implemented concession systems is large: as such the output from any one concession system will have negligible effects on price.

of the instrument (tenure length, target stock requirements) on its performance. We will obtain sharp analytical results by exploiting the structure of our dynamic and spatial game. We will derive closed form expressions of the owners' optimal payoffs when committing to the instrument, and when following their best defection strategies. This is necessary to analytically assess the performance of the instrument. We formally analyze the case of stock-dependent costs in Section 5.2.[13]

3.1.1 Social Planner's Problem

Our benchmark is the case of the social planner who maximizes the net present value of profit across the entire domain given the discount factor δ. Her objective is:

$$\max_{\{e_{1t},\dots,e_{Nt}\}} \sum_{t=0}^{\infty} \sum_{i=1}^{N} \delta^t p_i \left(x_{it} - e_{it}\right), \tag{7}$$

subject to the equation of motion (5) for each patch $i = 1, 2, ..., N$. Focusing on interior solutions, in any patch i, the planner should achieve the residual stock level:

$$g_i'\left(e_{it}^*\right) = \frac{p_i}{\delta \sum_j D_{ij} p_j} \tag{8}$$

The optimal residual stock results from the trade-off between the present profits from harvest and the discounted sum of future benefits given growth and dispersal to all patches. Note, by inspection, that these optimal residual stock levels are time and state independent. Thus, each patch has a single optimal residual stock level that should be achieved every period into perpetuity satisfying, for any period t:

$$e_{it}^* = e_i^*. \tag{9}$$

Since biological growth, dispersal, and economic returns are patch-specific, the optimal policy will vary across patches. Equation 8 highlights that this policy depends on patch-specific net prices, growth, and dispersal and self-retention parameters.

Let us discuss the assumption of interior socially optimal policies. This case is considered as it is consistent with the sustainable management of the resource. It allows us to emphasize the importance of ecological and economic fundamentals on the performance of the instrument. Technically, this is equivalent to assuming $g_i'(0) > \frac{p_i}{\delta \sum_j D_{ij} p_j}$ and $x_{i0} > (g_i')^{-1}\left(\frac{p_i}{\delta \sum_j D_{ij} p_j}\right)$ are satisfied, that is, marginal growth

[13]This corresponds to cases where resource rents are not constant: situations where the resource price is either time or stock dependent are also consistent cases.

$g_i'(0)$ and initial stock level x_{i0} lie above minimum threshold values. This second assumption may actually be consistent with cases where the resource is initially over-exploited. Indeed, socially optimal policies correspond to the benchmark case. By contrast, in Section 3.1.2 we will characterize the decentralized case, and highlight that the resulting extraction levels are higher than the socially optimal levels: thus, in the decentralized reference setting, the resource is generically over exploited. We will then show that our instrument can address this over-exploitation problem.

We conclude this section by discussing certain specific cases that can be addressed by our instrument. First, the polar case where social efficiency requires $e_{it}^* = 0$ $\forall t \geq 0$ in some patches can be addressed by our instrument. Indeed, if this is the case for some patches, then the marginal incentives of these patches' owners in the decentralized situation correspond to this case too. Second, the other polar case, where $e_{it}^* = x_{it}$ $\forall t \geq 0$ for at least one patch i, cannot be addressed by our instrument or by any concession instrument. Specifically, if one wants to implement the entire socially optimal paths, this would require combining our instrument with a side-payment scheme. However, in cases where socially optimal policies eventually become interior, an amended version of our instrument can induce these policies, starting from the first time period at which the socially optimal residual stock levels become interior in all patches.[14]

3.1.2 Decentralized Perpetual Property Right Holders

The second regime is the case in which each patch is owned in perpetuity by a single owner who seeks to maximize the net economic value of harvest from his patch, with complete information about the stock, growth characteristics, and economic conditions present throughout the system. In that case owner i solves:

$$\max_{\{e_{it}\}} \sum_{t=0}^{\infty} \delta^t p_i \left(x_{it} - e_{it} \right). \tag{10}$$

subject to the equation of motion (5). Following Lemma 1 in Kaffine and Costello (2011), at the subgame perfect Nash equilibrium owner i will always harvest down to a residual stock level $\bar{e}_{it}$ that satisfies:

$$g_i'(\bar{e}_{it}) = \frac{1}{\delta D_{ii}}. \tag{11}$$

We thus assume that the decentralized situation correspond to an interior equilibrium outcome: this requires that $g_i'(0) > \frac{1}{\delta D_{ii}}$ and $x_{i0} > (g_i')^{-1} \left(\frac{1}{\delta D_{ii}} \right)$ be satisfied. Thus,

[14] We will describe the corresponding amended form of the instrument in Section 4.

marginal growth $g_i'(0)$ is assumed to lie above a minimum threshold value. This is here assumed to keep the exposition as simple as possible, and our instrument can address cases where this does not hold. Moreover, as socially optimal policies are assumed to be interior (see Section 3.1.1), the condition on the initial stock level is satisfied already.

At the equilibrium outcome, the owner takes other owners' behaviors as given and realizes that he will not be the residual claimant of any conservative harvesting behavior. Thus, he behaves as if any additional resource that disperses out of his patch will be lost (indeed it will be harvested by his competitors). This is why the only dispersal term to enter the optimal residual stock term is D_{ii}, the fraction of the resource that remains in his patch. It is straightforward to show that $\bar{e}_{it} \leq e^*_{it}$ (with strict inequality as long as $D_{ii} \neq 1$): achieving social efficiency requires some kind of intervention or cooperation. Moreover, Equation (11) implies that $\bar{e}_{it} = \bar{e}_i$ for any time period.[15]

3.1.3 Decentralized, Limited-Tenure Property Rights

In the final regime, and the one on which we focus in this paper, we assume that ownership over patch i is granted to a private concessionaire for a duration of $\mathcal{T}_i$ periods, to which we will refer as the "tenure block" for the concession. All concessionaires have the possibility of renewal provided that certain conditions are met. Indeed, it is the possibility of renewal that will ultimately incentivize the concessionaire to deviate from her (excessively high) privately-optimal harvest rate; we will leverage this fact to design concession contracts to induce efficient outcomes. We begin by defining an arbitrary set of instrument parameters.

Definition 1. *The* Limited-Tenure Concession Instrument *is defined by a "target stock," $\mathcal{S}_i$, and a tenure period, $\mathcal{T}_i$ for concessionaire i.*

The concessionaire is allowed to extract as much of the resource as she wishes over her tenure block, and the regulator imposes only one rule on the concessionaire: At the end of the tenure block (i.e. at time $\mathcal{T}_i - 1$, since the block starts at $t = 0$), the concession will be renewed (under terms identical to those of the first tenure block) if and only if the resource stock is maintained at or above the target stock ($\mathcal{S}_i$) in every period. So, concession i will be renewed if and only if:

$$e_{it} \geq \mathcal{S}_i \qquad \forall t \leq \mathcal{T}_i - 1. \tag{12}$$

[15] As shown in Kaffine and Costello (2011), this result actually implies that the open loop and feedback control rules are identical.

Keep in mind that the renewal requirement is defined with respect to the stock level of the resource at the *end* of any given time period: the residual stock level in patch i at a given time period t, namely e_{it}, must lie above the target stock S_i. Note that we allow for this instrument to be explicitly spatial in the sense that $\mathcal{S}_i \neq \mathcal{S}_j$.

Beyond the enforcement of the concession contract, the regulator plays no role in the management of the resource; all harvest decisions are made privately by the concessionaire. Because the regulator would like to replicate the social planner's solution (see Section 3.1.1), she must determine a set of target stocks in each area $\{\mathcal{S}_1, \mathcal{S}_2, ..., \mathcal{S}_N\}$ and tenure lengths $\{\mathcal{T}_1, \mathcal{T}_2, ...\mathcal{T}_N\}$ (i.e., a $\{\mathcal{S}_i, \mathcal{T}_i\}$ pair to offer concessionaire i) that will incentivize all concessionaires to simultaneously, and in every period, deliver the socially optimal level of harvest in all patches. We will restrict attention to tenure lengths that are the same for all concessionaires, so $\mathcal{T}_i = T$, $\forall i$.[16]

We will show that, if designed properly, limited-tenure concessions can be used to induce concessionaires to manage resources in a socially optimal manner. Agents may, or may not, comply with the terms of the concession contract. If all N concessionaires choose to comply with the target stocks in every period of every tenure block, we refer to this as *cooperation.* All owners will then earn an income stream in perpetuity. Instead, if a particular owner i fails to meet the target stock requirement (i.e, in some period she harvests the stock below $\mathcal{S}_i$), then, while she will retain ownership for the remainder of her tenure block (and thus be able to choose any harvest over that period), she will certainly not have her tenure renewed. In that case, owner i's payoff will be zero every period after her current tenure block expires. Thus, the instrument raises a trade-off for each concessionaire who chooses whether to cooperate or to defect. Since an owner's payoff depends on others' actions, we assume that if concessionaire i defects, then the concession is granted to a new concessionaire in the subsequent tenure block. If all initial owners decide to defect and are not renewed at the end of the current tenure, then the game ends.[17]

3.2 Cooperation vs. Defection

We now characterize (i) the payoffs that each concessionaire could achieve under cooperation, and (ii) the concessionaires' best defection strategies.

[16]Intuitively, since concessionaires are heterogeneous, tenure lengths could be heterogeneous as well. In order to limit the complexity of the scheme, and because the use of a uniform tenure length for renewal seems to be the norm for real-world cases of concessions-regulated resources, we consider the longest tenure that is compatible with all concessionaires' incentives to cooperate. This characterization is provided by expression 18 in Section 4.

[17]This rule is irrelevant: as we later show, if everyone defects, the resource is driven extinct.

We first consider that all N concessionaires cooperate and thus comply with the target stocks in every period of every tenure block. Provided they do not exceed the target stock (they do not over-comply), then concessionaire i's payoff is:

$$\Pi_i^c = p_i \left[x_{i0} - \mathcal{S}_i + \sum_{t=1}^{\infty} \delta^t \left(x_i^* - \mathcal{S}_i \right) \right]. \tag{13}$$

where x_{i0} is the (given) starting stock and $x_i^* = \sum_j D_{ji} g(\mathcal{S}_j)$.

We turn to the characterization of the concessionaires' best defection strategies. If concessionaire i defects during an arbitrary tenure block k and all other concessionaires follow their equilibrium strategies (that is, they cooperate), concessionaire i's best defection strategy is characterized in the following result.[18]

Proposition 1. *1. First assume that* $\frac{p_i}{\delta \sum_j D_{ij} p_j} < g_i'(0) \leq \frac{1}{\delta D_{ii}}$. *Then the best defection strategy of concessionaire i in tenure block k is given by $\bar{e}_{it} = 0$ for any period $(k-1)T \leq t \leq kT - 1$.*

2. Second, assume that $g_i'(0) > \frac{1}{\delta D_{ii}}$. Then the best defection strategy of concessionaire i in tenure block k is characterized as follows:

$$\bar{e}_{ikT-1} = 0$$

and, for any period $(k-1)T \leq t \leq kT - 2$, we have $\bar{e}_{it} = \bar{e}_i > 0$ where:

$$g_i'(\bar{e}_i) = \frac{1}{\delta D_{ii}} \quad \textit{with } \bar{x}_i = D_{ii} g(\bar{e}_i) + \sum_{j \neq i} D_{ji} g(\mathcal{S}_j) > \bar{e}_i.$$

When marginal growth $g_i'(0)$ is sufficiently low in area i, a concessionaire who decides to defect *sometime* during tenure block k, will completely mine the resource in his patch at every period of the tenure block. By contrast, when marginal growth is high enough, this defecting concessionaire will (1) choose the non-cooperative level of harvest (see Section 3.1.2) up until the final period of the tenure block and (2) then completely mine the resource.[19] Either way, the resource is completely mined in that patch by the end of the tenure block. Note that the best defection strategy does not depend on the tenure block, k. This finding simplifies the characterization of equilibrium strategies. The present value of owner i's defection payoffs is:

[18] The proof relies on backward induction arguments since defection would occur on one tenure block, and the defecting agent would not be renewed again.

[19] Note that if only one concessionaire defects, the entire stock will not be driven extinct because patch i can be restocked via dispersal from patches with owners who cooperated.

$$\Pi_i^d = p_i \left[x_{i0} - \mathcal{S}_i + \sum_{t=1}^{(k-1)T-1} \delta^t \left(x_i^* - \mathcal{S}_i \right) + \delta^{(k-1)T} \left(x_i^* - \bar{e}_i \right) + \sum_{t=(k-1)T+1}^{kT-2} \delta^t \left(\bar{x}_i - \bar{e}_i \right) + \delta^{kT-1} \bar{x}_i \right] \tag{14}$$

Expression (14) follows from Proposition 1. The payoff when patch owner i defects during tenure block k is given by (1) the profit obtained while abiding by the target stock prior to the k^{th} tenure block (the first two terms on the right-hand side of equality (14)), and (2) the profit from non-cooperative harvesting during tenure block k (the third and fourth terms on the RHS of equality (14)), until finally extracting all the stock in the final period of the k^{th} tenure block, $kT-1$ (the fifth and final term on the RHS of equality (14)). We will make extensive use of the defection strategy in what follows. We next turn to the conditions ensuring cooperation.

4 Conditions for Cooperation

Here we derive the conditions under which all N concessionaires willingly choose to cooperate in perpetuity. We proceed in three steps. First, we derive the target stocks that must be announced $(\mathcal{S}_1, ..., \mathcal{S}_N)$ by the regulator who wishes to replicate the socially optimal level of extraction in every patch at every time, and we derive necessary and sufficient conditions for cooperation to be sustained. Second we discuss the effects of the patch-level parameters. Finally, we assess the influence of the tenure duration T on the emergence of cooperation, and provide comparative statics results.

4.1 The emergence of cooperation

Our interest here is to design the concession instrument to replicate the socially-optimal harvest in each patch at every time. We first prove that the regulator *must* announce, as a patch-i target stock, the socially-optimal residual stock for that patch.

Lemma 1. *A necessary condition for social optimality is that the regulator announces: $\mathcal{S}_1 = e_1^*$, $\mathcal{S}_2 = e_2^*$,..., $\mathcal{S}_N = e_N^*$, where e_i^* is given in Equation 8.*

Lemma 1 relies on two main results from above. First, because $\bar{e}_i \leq e_i^*$, if the regulator announces any $\mathcal{S}_i < e_i^*$, then the concessionaire will optimally drive the stock below e_i^*, which is not socially optimal. Second, if the regulator sets a high target, so $\mathcal{S}_i > e_i^*$, then the concessionaire either complies with the target (and the stock is inefficiently high) or defects and reaches an inefficiently low target stock. Thus, Lemma 1 provides the target stocks that must be announced.

Thus, we can restrict attention to the target stocks $\mathcal{S}_i = e_i^* \ \forall i$. In that case, compliance by concessionaire i requires that $e_{it} \geq e_i^* \ \forall t$, so she must never harvest below that level. Our next result establishes that, while concessionaire i is free to choose a residual stock that *exceeds* e_i^*, she will never do so.

Proposition 2. *If concessionaire i chooses to cooperate, she will do so by setting $e_{it} = e_i^* \ \forall i, t$.*

Proposition 2 establishes that, if it can be achieved, cooperation involves each concessionaire leaving precisely the socially-optimal residual stock in each period.[20]

We now proceed as follows. We characterize the conditions ensuring that any given concessionaire i lacks incentives to defect from the strategy characterized by Proposition 2 when all other concessionaires follow this strategy.[21] In any given tenure block, the decision facing concessionaire i is whether or not to comply with the target stock requirement in each period. When all other concessionaires follow the strategy characterized by Proposition 2, one simply calculates her payoff from the best defection strategy (see Proposition 1) and compares it to her payoff from the cooperation strategy. We define concessionaire i's *willingness-to-cooperate* by:

$$W_i \equiv \Pi_i^c - \Pi_i^d. \tag{15}$$

Reminiscent of Folk-Theorem results in repeated games (see Mailath and Samuelson (2006)), we find that each concessionaire must trade off between a *mining* effect, in which she achieves high short-run payoffs from defection during the current tenure block, and a *renewal* effect, in which she abides by the regulator's announced target stock, and thus receives lower short-run payoff, but ensures renewal in perpetuity. This comparison turns out to have the following straightforward representation:

Proposition 3. *Cooperation emerges as an equilibrium outcome if and only if, for any concessionaire i, the following condition holds:*

$$\delta x_i^* - e_i^* > \left(1 - \delta^{T-1}\right)\left(\delta \bar{x}_i - \bar{e}_i\right). \tag{16}$$

Condition 16 is the analog to Condition 4, which was derived in the simple case of private provision of public goods. Specifically, Proposition 3 shows that the gains

[20]When there exists a time period t_0 such that $e_{it}^* = x_{it} \ \forall t \leq t_0$ and $e_{it}^* < x_{it}$ thereafter for any patch i, one can design a concession instrument inducing the socially optimal path starting at $t = t_0 + 1$. It would be defined as follows: $\forall t \leq t_0$ we have $S_{it} = \bar{S}_i < x_{it}$ (where this target level is characterized depending on the fundamentals of the setting) and $\forall t \geq t_0 + 1$ we have $S_{it} = e_i^*$.

[21]These conditions ensure that the socially optimal outcome constitutes an equilibrium outcome.

from cooperation to concessionaire i $(\delta x_i^* - e_i^*)$ must be sufficiently large compared to those corresponding to defection $(\delta \bar{x}_i - \bar{e}_i)$. In such cases, we get cooperation forever.[22] Consider the case when concessionaires are patient, and thus the discount factor, δ, is high. Then the right-hand side of Condition 16 gets close to zero, and the left-hand side to $x_i^* - e_i^*$, so as long as we have an interior solution to the optimal spatial problem, the condition holds. On the contrary, when concessionaires are impatient (so the discount factor gets close to zero), keeping in mind that $e_i^* > \bar{e}_i$, cooperation never arises. These cases are used as examples: there are cases (depending on spatial parameters) where Condition 16 holds generically without assuming sufficiently patient concessionaires.

We show that the concession instrument we propose can lead to efficient extraction across space and time in perpetuity. But this relies on a relatively strict enforcement system (an owner who defects is not renewed). Because the welfare gains from cooperation vs. non-cooperation are potentially large, less stringent systems might also lead to efficient behavior. Yet, the renewal process adopted here is consistent with the main characteristics of real-world cases of concessions-regulated resources. Our analysis highlights that, even without accounting for additional incentives (financial penalties), limited-tenure concessions have attractive practical appeal.[23]

4.2 Effects of Patch-Level Characteristics

Naturally, patch-level characteristics will affect a concessionaire's payoffs and may therefore play a role in the decision of whether to defect or cooperate. The fact that patch-level characteristics may also affect the announced target stocks further complicates the analysis. We next examine the effects of price, growth, and dispersal on the concessionaire i's *willingness-to-cooperate*, defined by Condition (15). As a parameter changes, we must trace its effects through the entire system, including how it alters others' decisions. Assuming that the willingness to cooperate is initially positive, the impact of prices $\{p_i, p_j\}$ is as follows: Concessionaire i's willingness-to-cooperate, W_i, is increasing in p_i, but is ambiguous in the price of the adjacent area, p_j, and depends on the degree of the connection between patches.

The effect of productivity of connected patches is also nuanced. Agent i will be more likely to cooperate with a higher growth rate of the adjacent property,

[22] The proof of Proposition 1 highlights that defection entails at least some harvest (the stock satisfies $\bar{x}_i = \sum_{j \neq i} D_{ji} g(e_j^*) + D_{ii} g(\bar{e}_i) > \bar{e}_i$). Thus, there are no corner solutions.

[23] Financial penalties may be infeasible in developing countries, as financial constraints may be tight. As the effect of financial capacity on natural resource management may be ambiguous (see for instance Tarui (2007) for an analysis of the effect of improved access to credit), relying on the concession instrument avoids potential problems related to the use of monetary devices.

α_j. Since defection implies harvesting one's entire stock, there is little opportunity (under defection) to take advantage of one's neighbor's high productivity. But under cooperation, a larger α_j implies larger immigration, which translates into higher profit. The impact of own growth (α_i) is negative when the self-retention rate, D_{ii}, is small, and is positive for sufficiently large D_{ii}. The direct impact on the residual stock in patch i offsets all other impacts, but as a small proportion of the resource stays in the area; this decreases the gains from cooperation.

Finally, spatial parameters have interesting implications. We provide cases in the Appendix where the cooperation decision is increasing in self-retention, D_{ii}, but its impact is mixed since it affects the resource stock under defection and cooperation. W_i, is increasing in D_{ji} for reasons similar to those driving comparative statics on α_j. In contrast, a higher emigration rate (D_{ij}) reduces the incentive to cooperate. The intuition is that defection incentives are not altered much (since concessionaire i harvests the entire stock under defection), but cooperation incentives are reduced because the regulator will instruct concessionaire i to reduce her harvest under a larger D_{ij}.

Table 1: Effect of patch-specific parameters on willingness-to-cooperate.

θ	p_i	p_j	α_i	α_j	D_{ii}	D_{ij}	D_{ji}
$\frac{\partial W_i}{\partial \theta}$	$+$	$+/-$	$+/-$	$+$	$+/-$	$-$	$+$

These results provide insight about how the strength of i's cooperation incentive depends on parameters. Whether this incentive is sufficiently strong to induce cooperation (i.e. whether $W_i > 0$) remains to be seen. We focus on resource dispersal, which plays a pivotal role here. If the resource was immobile, the patches would not be interconnected, and private property owners with secure property rights would harvest at a socially optimal level in perpetuity. Dispersal undermines this outcome and induces a spatial externality which leads to overexploitation. Thus, the nature and degree of dispersal will play an important role in each concessionaire's cooperation decision.

In this model, dispersal is characterized by the NxN matrix whose rows sum to something less than or equal to 1 ($\sum_j D_{ij} \leq 1$). There are N^2 free parameters that describe dispersal, so at first glance it seems difficult to get general traction on how dispersal affects cooperation. But Proposition 1 provides a useful insight: *If concessionaire i decides to defect, she will optimally do so by considering only D_{ii}, thus ignoring all other $N^2 - 1$ elements of the dispersal matrix.* This insight allows first to assess the effect of spatial parameters on the emergence of cooperation. We show that a high degree of self-retention (D_{ii}) in all patches – that is a situation with low migration rates – is sufficient to ensure cooperation.

Proposition 4. *Let patch i be the patch with* <u>*smallest*</u> *self-retention parameter. For sufficiently large D_{ii}, cooperation over all N concessions can be sustained as an equilibrium outcome.*

Intuitively, if all patches have sufficiently high self-retention, then the externality across patches is relatively small, which (we show) implies that the *renewal* effect outweighs the *mining* effect in all patches. When spatial externalities are not too large, the concession instrument overcomes the externality caused by strategic interaction. If self-retention is very low, then a large externality exists, and it may be more difficult to sustain cooperation. The formal result is not quite as straightforward because D_{ii} also plays a role in e_j^* for *all* patches j, and thus affects defection incentives in all patches. Accounting for all of these dynamics, we obtain:

Proposition 5. *Let patch i be the patch with the* <u>*largest*</u> *self-retention parameter. For sufficiently small D_{ii}, cooperation will not emerge as an equilibrium outcome provided the following condition is satisfied:*

$$p_i \sum_{j \neq i} D_{ji} g(e_j^*) < \sum_{j \neq i} D_{ij} p_j g'(e_i^*) e_i^*. \tag{17}$$

Proposition 5 establishes that if the resource is highly mobile (sufficiently low self-retention rates), then cooperation might be destroyed. This result relies on the fact that economic benefits mainly depend on resource immigration. Condition (17) compares concessionaire i's cooperation benefits due to incoming resources and the sum of benefits others may get from the resource migrating from patch i. This condition contrasts the benefits and losses of concessionaire i due to species movement.

4.3 Effect of tenure duration

Thus far we have focused on inherent features of the system as a whole that affect a concessionaire's incentives to cooperate or defect. But Condition (16) also depends on the tenure length T. Indeed, this parameter might play a role in how concessionaires make their private decisions, and thus this is a policy issue for a concession regime to be successful. We now focus on the optimal determination of T.

A basic tenet of property rights and resource exploitation is that more secure property rights lead to more efficient resource use. Costello and Kaffine (2008) found that longer tenure duration indeed increased the likelihood of sustainable resource extraction in limited-tenure (though aspatial) concessions. So at first glance, we might expect a similar finding here. In fact, we find the opposite:

Proposition 6. *For sufficiently long tenure duration, T, cooperation cannot be sustained as an equilibrium outcome.*

Proposition 6 seems to contradict basic intuition; it states that if tenure duration is long, it is impossible to achieve socially-optimal extraction of a spatially-connected resource by using our instrument. But upon deeper inspection this result accords with economic principles, due to defection incentives driven by spatial externalities, while such effects are absent in the setting considered in Costello and Kaffine (2008). Consider the case of very long tenure duration - in the extreme, when tenure is infinite, gains from defection always outweigh gains from cooperation. The promise of renewal has no effect on incentives, so each concessionaire acts in his own best interest, which involves the defection path identified in Proposition 1.[24] Proposition 6 also holds in an extended version of the instrument, where the regulator can (with some probability $f < 1$) terminate tenure immediately upon defection (rather than waiting until the end of the tenure block in which defection occurs).[25] Indeed, the best defection will retain the features of Proposition 1: $\bar{e}_{it} = \bar{e}_i(f) > 0$ at every period but the last one, and $\bar{e}_{ikT-1} = 0$ (as long as $1 - f$ is large enough so that $\bar{e}_i(f) > 0$ holds). Since cooperation payoffs remain unchanged, results in Proposition 3 and thus Proposition 6 remain valid under this extension. Other interpretations of this extension are interesting. On one hand, f could reflect stock assessment uncertainty (so f is the probability of correct assessment). Then the instrument is robust to imperfect stock assessment (when f is large enough). On the other hand, if it denotes the probability that stock assessment is actually implemented, then the expected monitoring cost would decrease as the tenure length increases. Thus, when it is costly to frequently monitor users' actions, and to revoke and reallocate rights upon defection, there is a trade-off for tenure duration: Long tenure duration might result in defection, while short duration might entail higher monitoring costs.

Short tenure duration harbors two incentives for cooperation: First, when tenure is short, the payoff from defection is relatively small because the concessionaire has few periods in which to defect. Second, the renewal promise is significant because it involves a much longer future horizon than does the current tenure block. This result obtains because the spatial externality of resource dispersal drives a wedge between the privately optimal decision and the socially optimal one.

In fact, we can characterize a threshold tenure length for which concessionaire i

[24] We focus on the incentives of any concessionaire when all other concessionaires follow the equilibrium strategies defined in Proposition 2. More complex strategies (trigger strategies) might weaken Proposition 6; we provide one related result (Proposition 10) in the Appendix.

[25] We maintain the assumption that, at the last period of the tenure block, the regulator can terminate tenure immediately upon defection with probability one.

will defect if $T_i > \bar{T}_i$, and owner i will cooperate otherwise. The time-threshold for concessionaire i can be written as follows:

$$\bar{T}_i = 1 + \frac{\ln\left(\frac{\delta(\bar{x}_i - x_i^*) + e_i^* - \bar{e}_i}{\delta\bar{x}_i - \bar{e}_i}\right)}{\ln(\delta)} \tag{18}$$

Consequently, it can be shown that cooperation is sustained by assigning to all N concessionaires a threshold value, which we summarize as follows:

Proposition 7. *Assume the following holds for concessionaire i:*

$$\delta x_i^* - e_i^* > (1-\delta)\left(\delta\bar{x}_i - \bar{e}_i\right); \tag{19}$$

Then there exists a threshold value $\bar{T} = \min_i\{\bar{T}_i\} > 1$ such that cooperation is sustained as an equilibrium outcome if and only if $T \leq \bar{T}$.

The condition in Proposition 7 is a restatement of Proposition 3 for a tenure period $T = 2$. Thus, we know that a tenure period of 1 will guarantee cooperation. Since the threshold tenure length, $\bar{T} = \min_i\{\bar{T}_i\}$, depends on patch level characteristics, we briefly examine its dependence on patch, and system-level characteristics.

Because $\bar{e}_i$, $\bar{x}_i$, e_i^*, and x_i^* all depend on model parameters, deriving comparative statics is non-trivial. Recalling the comparative statics which addresses how concessionaire i's willingness to cooperate depends on parameters of the problem, intuitively similar results will be obtained here. Indeed, we obtain qualitatively similar results, and we relegate them to the Appendix (in Section B).

5 Further results and discussions

To maintain analytical tractability, and to sharpen the analysis, we have relied on a number of simplifications. Here we examine the consequences of three noteworthy assumptions. First, we assess the effect of a finite horizon on incentives to cooperate. Then, we discuss the cases of, respectively, stock-dependent costs and density-dependent dispersal. We move on to discussing the issue of stock assessment and monitoring and, finally, we compare our instrument with other potential policies.

5.1 The case of a finite horizon

In this analysis, concessionaires must trade off a finite single tenure block against an infinite number of renewed tenure blocks. It raises the question of whether the instrument is still effective at inducing cooperation when the horizon is finite. Suppose time ends after K tenure blocks where $1 < K < \infty$ after which all concessionaires' payoffs are zero. We prove here that cooperation remains subgame perfect under the finite horizon problem, but that this requires more stringent conditions.

Proposition 8. *Suppose time ends after the K^{th} tenure block. Provided that the following condition holds for any i:*

$$\left(1-\delta^{T}\right)\left(\delta x_i^* - e_i^*\right) - \delta^{T}\left(1-\delta^{T-1}\right)\left(\delta \bar{\bar{x}}_i - \bar{e}_i\right) > \left(1-\delta^{T-1}\right)\left(\delta \bar{x}_i - \bar{e}_i\right), \qquad (20)$$

then the instrument induces cooperation for the first $K-1$ tenure blocks.[26] *This condition is more stringent than the one ensuring cooperation over an infinite time horizon.*

Proposition 8 states that the time horizon need not be infinitely long for our instrument to be effective: yet this requires more stringent conditions. Indeed, condition (20) is a new statement of the condition provided in Proposition 3. The right-hand side term (the gains from defection) remains the same, while the left-hand side term is more complex. Concessionaires anticipate that they will not be renewed at the end of the final tenure block: they follow the cooperative strategy during the first tenure blocks, then they *all* defect and choose residual stock $\bar{e}_i$ before mining the resource in the final period. The cooperation payoffs during the entire process, $\left(1-\delta^{T}\right)\left(\delta x_i^* - e_i^*\right)$, are now lower due to the increase in the defection payoffs in the final period $\delta^{T}\left(1-\delta^{T-1}\right)\left(\delta \bar{\bar{x}}_i - \bar{e}_i\right)$. In other words, shorter time horizons require more stringent conditions for cooperation to be effective. Thus, longer time horizons (not to be confused with longer tenure durations) are most effective.

5.2 Stock-dependent costs

So far, we assume that extraction costs are linear in the amount extracted. Here we relax this assumption. Concessionaire i's period-t payoffs then become:

$$\Pi_{it} = p_i\left(x_{it} - e_{it}\right) - \int_{e_{it}}^{x_{it}} c_i(s)ds$$

where $c_i'(s) < 0$ is continuously differentiable (see Reed (1979) for an early treatment of stock-dependent costs). We now explain briefly why the logic of Proposition 3 (about the performance of the instrument) remains valid here. The proof relies mainly on two arguments, full details are available in the appendix in Propositions 11 and 12. First, the best defection strategy does not depend on the tenure block

[26] Expression $\bar{\bar{x}}_i$ is defined as $\bar{\bar{x}}_i = \sum_j D_{ji} g\left(\bar{e}_j\right)$.

considered. Second, for the tenure block during which defection occurs, patch owner i's best defection strategy in period t remains time and state independent.[27] Thus, even though the characterization of the best defection strategy differs, and so the conditions ensuring the emergence of cooperation differ from Conditions (16), the qualitative conclusion of Proposition 3 still remains valid.

There is one interesting qualitative difference though. When costs are stock independent, an agent (say i) who would choose to defect would eventually drive the resource to extinction in his own patch. By contrast, if costs do depend on stock levels, agent i does not drive the resource to extinction if he chooses to defect, but he harvests it down to level $c_i^{-1}(p_i) > 0$. The proof of Proposition 12 highlights that this has a negative effect on this agent's incentives to defect. Thus, the assumption of stock-dependent costs, through its negative effect on defection incentives, would make cooperation easier to sustain compared to the case of stock-independent costs.

Overall, since a similar logic applies, other main findings (for instance, the failure of the instrument for sufficiently long tenure lengths) are unlikely to be overturned.

5.3 Stock dependent dispersal

We assume so far that the dispersal process does not depend on residual stock levels. We now relax this assumption. Thus, we define for any patch i the law of motion as $x_{it+1} = \sum_j D(e_{jt})g_j(e_{jt})$ which models density-dependent dispersal, and where $D(e_{it})$ denotes the difference between self-retention and dispersal rate.

In this amended version of the model, following Costello and Polasky (2008) it is easily checked that the socially-optimal policy still remains time and state independent. Moreover, the characterization of the best defection strategy follows from backward induction arguments as in Section 3.2: assuming defection occurs at tenure $k+1$, we obtain $e_{i(k+1)T-1} = 0$ and then, for any preceding time period t in tenure $k+1$, we have $e_{it} = \hat{e}_i$ satisfying

$$-1 + \delta \left[D'(e_{it})g_i(e_{it}) + D(e_{it})g_i'(e_{it})\right] = 0$$

This condition highlights two effects: a direct effect on marginal productivity, which might result in higher or lower defection strategy, and an indirect effect on dispersal, which tends to increase benefits from higher in-migration if one assumes negative density-dependent dispersal. Specifically, we deduce:

$$g_i'(\hat{e}_i) = \frac{1 - \delta D'(\hat{e}_i)g_i(\hat{e}_i)}{\delta D(\hat{e}_i)} \tag{21}$$

[27] These properties are proved in the Appendix, and rely on backward reasoning arguments.

We now highlight that, compared to the case of density-independent dispersal, it is more difficult to induce cooperation when dispersal negatively depends on density. Specifically, denoting $D_{ii} \equiv D(\hat{e}_i)$ we obtain the following result:

Proposition 9. *Let us consider $\hat{e}_i$ the solution to condition (21). Then we have $\hat{e}_i < \bar{e}_i$, where $\bar{e}_i$ denotes agent i's best defection strategy under density-independent dispersal when self-retention rate in patch i is given by D_{ii}. As such, the defection payoff increases, and the conditions for cooperation becomes in turn more stringent under density-dependent dispersal.*

Since the optimal defection strategy yields higher payoffs under density-dependent dispersal, it becomes more difficult to sustain cooperation.

5.4 Stock assessment and monitoring

We have assumed that the regulator can monitor the stock to verify compliance with the terms of the concession contract. In practice, stock assessment may be difficult to implement, and the cost of monitoring may thus prove important. Several points are worth highlighting. First, the alternative form of the instrument discussed in Section 4.3 exhibits some robustness to imperfect stock assessment; moreover, it would actually decrease the expected cost of monitoring. Indeed, it accounts for the fact that the probability that stock assessment is actually implemented may be less than one, and the expected monitoring would thus decrease as the tenure length increases.[28]

Second, several contributions suggest that regular stock assessment is a mandatory part of a well-designed concession system, even if it is based on extraction levels. In successful systems an annual stock assessment is carried out by technical consultants approved by the government and paid by concession members.[29] This requirement is further supported by Hilborn et al. (2005): successful concession systems based on extraction levels tend to engage in active research programs funding stock assessments. Thus, for a system to be effective, proper stock assessment is mandatory, whether the system is based on extraction or on (residual) stock requirements.

Moreover, endogenous enforcement might be strengthened by parameters inducing persistent cooperation over time, particularly when monitoring involves capital expenditures.[30] Enforcement issues may be driven by lack of legitimacy or the "need"

[28]The same conclusion holds in the public good setting when monitoring is costly.

[29]See Wilen et al. (2012) for a discussion.

[30]Concession rights might strengthen endogenous enforcement, and this could be rewarded via management certification, which may in turn provide improvements in market access. Thus, certifi-

for profit versus risk of deterrence. In developing countries this motivation might be greater than in developed ones; this might underscore enforcement issues. Yet, initiatives like community-based concessions might improve legitimacy while reducing monitoring costs.[31] These institutional arrangements are receiving increasing attention in developing countries. Since participation in the organization of the concession instrument can contribute to its legitimacy, such concessions might be interesting to increase enforcement in such areas. Finally, real-world cases suggest that science-based stock assessment is an integral part of the property rights system, which makes it less onerous for managers to monitor stocks and assess patch-specific characteristics. Cooperation between communities and government might help to decrease the cost of stock assessment, providing incentives for engagement in assessment practices (Hilborn et al. (2005)). Indeed, it allows increasing interactions between concession owners and public-sector scientists, who might contribute to stock assessment, thus decreasing the assessment cost in return for access to the data collected.

Finally, if stock assessments require a fixed cost each year, then they also influence the social planner's optimized payoff, but will not affect her optimal choice of residual stock. This follows from Section 3.1.1. This will also be the case for concessionaires under the concession instrument proposed here: their optimized payoffs will be affected, but their optimal choice to cooperate/defect will not. In other words, the existence of monitoring costs will affect the agents' optimized payoff, but it will not affect the ability of the instrument to act as an effective cooperation device.

5.5 Comparison with other potential policies

Our paper explicitly compares three alternative policies. First, we examine the social planner's problem: externalities are internalized and the result is Equation 4 in each and every patch, which yields the highest possible present value of the spatially-connected resource. Second, we examine the completely decentralized policy where property rights are allocated, but without coordination across properties. This leads to over-extraction in all patches (as shown in Equation 7). Finally, we examine a wide range of possible concession instruments (longer and shorter tenure duration, higher and lower target stocks). We derive the parameters of the concession contract that guarantee that the socially optimal extraction level will take place every period.

cations might decrease transaction costs and strengthen agents' monitoring activities; both mechanisms would plausibly ease the conditions under which our instrument induces the efficient outcome.

[31] Monitoring costs are likely to be lower compared to the case of state monitoring. Legitimacy may increase because of active and engaged leadership (Crona et al. 2017).

One might consider alternative concession approaches, though a full comparison is beyond the scope of this paper. One candidate is to consider concessions with renewal based on maximum total extraction. The characterization of the socially optimal paths obtained in Section 3.1.1, together with the characterization of the best defection path in Proposition 1, suggest that this instrument would not achieve the socially optimal outcome. Even if total extraction requirements are satisfied by the end of the tenure, it will induce over-harvest in certain time periods. Thus, it cannot ensure that the socially optimal outcome is implemented at any time period.

Second, consider that renewal is based on the maximum total extraction in any time period. This would be similar to our proposed system, except that the tenure renewal requirements would be based on extraction target levels every time period, rather than a target stock. If one focuses on the capacity of this instrument to induce the socially optimal outcome, then the conditions under which it is effective are likely to be equivalent to those related to our instrument. Indeed, by the identity $h_{it} = x_{it} - e_{it}$, one could choose either extraction or residual stock as the main defining variable (given the state of the system ($\mathbf{x}_t$) one derives from the other). Moreover, as discussed in Section 5.4, both instruments require regular stock assessment.

Third, consider policies that employ property rights over the resource rather than over space. This approach induces challenges for spatial resources because biological growth, dispersal, and economic returns are patch-specific, and the optimal policy will thus vary across patches. Equation 8 reveals that the optimal policy depends on patch-specific net prices, growth, and dispersal and self-retention parameters. So the socially optimal outcome is spatially explicit, while using property rights over the resource implies that one proposes a non-spatial instrument. Thus, it cannot achieve the first best, unlike our proposed instrument. Furthermore, as explained in Section 5.4 it is not clear that such system would be less demanding in terms of the related monitoring costs if the manager wants this policy to be as effective as possible.[32]

Finally, while the size of concessions is not endogenously chosen here, this dimension might be part of the manager's decision. If size is somehow related to biological productivity, then the findings from Section 4.2 suggest that variations in the size of connected patches may have complex effects. Indeed, agent i's willingness to cooperate increases as the size of an adjacent property increases, but the effect of an increase in the size of agent i's own property on his incentives to do so is ambiguous.

[32]See Wilen et al. (2012) for other advantages of spatially explicit instruments.

Such a policy would then have to account for a variety of direct and indirect effects. This will raise many new questions about design and effectiveness.

6 Conclusion

We have analyzed the ability of limited-tenure concessions to incentivize socially-efficient private provision of collective goods. We show this in a public goods contribution setting and in the more complicated natural resource extraction setting with resource growth, mobility, and heterogeneity across space. This may be surprising, as it does not rely on any transfers or side-payments, and though it does accord with some real-world institutions that either use such instruments to manage natural resources or use fairly similar systems to manage public goods. They work so effectively because they offer the promise of concession renewal, but only if socially-optimal extraction has been undertaken in the past. Thus, if well-designed, concessionaires will find best to adhere to socially-optimal extract or contribution (and achieve renewal) rather than to over-extract (or under-contribute) in the short run (and fail to achieve renewal). Unlike an initial intuition, longer tenure actually induces greater overextraction (or greater under-contribution). This implies that there is an optimal tenure length, which we derive in the paper.

Several observations bear further discussion. First, we consider a quite secure system: renewal is ensured as long as the target is attained. This allows to focus on the effects of the spatial characteristics of our problem. Introducing a renewal probability would require characterizing the threshold value over which cooperation could be induced; a version of this approach was discussed in Section 4.3.

Second, several extensions remain, we present them for the case of common-pool resources. There could be imperfect (incomplete) information, or the resource growth could be stochastic. As long as patches are symmetric regarding the anticipated effects, we expect no drastic change in the qualitative results. The regulator's or manager's incentives in offering concessions may also be an interesting issue. In this setting, the regulator could be viewed as a Stackelberg leader. The focus here was on identifying design parameters that induce concessionaires to cooperate. A next step could involve introducing different regulators' objectives. Finally, depending on the situations there could be different timing of growth. This reduces model tractability and neither renders our results moot nor obviously makes the analysis more realistic.

Overall, our results suggest that limited tenure concessions can achieve optimal outcomes and yet still allow concessionaires to make decentralized decisions all while the regulator retains authority to require adherence to certain restrictions. They also suggest that concessions may not only have attractive intuitive appeal: if designed with care, they could be theoretically grounded in economic efficiency.

References

Aburto-Oropeza, O., H. Leslie, A. Mack-Crane, S. Nagavarapu, S. Reddy, and L. Sievanen (2017). Property rights for fishing cooperatives: How (and how well) do they work? *World Bank Economic Review 31*, 295–328.

Berglas, E. (1976). On the theory of clubs. *American Economic Review 66*, 116–121.

Bergstrom, T., L. Blume, and H. Varian (1986). On the private provision of public goods. *Journal of Public Economics 29*, 25–49.

Buchanan, J. (1965). An economic theory of clubs. *Economica 32*, 1–14.

Cheung, S. (1970). The structure of contract and the theory of a non-exclusive resource. *Journal of Law and Economics 13*, 49–70.

Cornes, R. and T. Sandler (1983). On commons and tragedies. *American Economic Review 73*, 787–792.

Cornes, R. and T. Sandler (1996). *The Theory of Externalities, Public Goods, and Club Goods*. Cambridge University Press.

Costello, C. and D. Kaffine (2008). Natural resource use with limited-tenure property rights. *Journal of Environmental Economics and Management 55*(1), 20–36.

Costello, C., D. Ovando, T. Clavelle, C. K. Strauss, R. Hilborn, M. C. Melnychuk, T. A. Branch, S. D. Gaines, C. S. Szuwalski, R. B. Cabral, et al. (2016). Global fishery prospects under contrasting management regimes. *Proceedings of the national academy of sciences 113*(18), 5125–5129.

Costello, C. and S. Polasky (2008). Optimal harvesting of stochastic spatial resources. *Journal of Environmental Economics and Management 56*, 1–18.

Costello, C., N. Quérou, and A. Tomini (2015). Partial enclosure of the commons. *Journal of Public Economics 121*, 69–78.

Crona, B., S. Gelcich, and O. Bodin (2017). The importance of interplay between leadership and social capital in shaping outcomes of rights-based fisheries governance. *World Development 91*, 70–83.

Demsetz, H. (1967). Towards a theory of property rights. *American Economic Review 52*(2), 347–379.

Fischer, C. and R. Laxminarayan (2010). Managing partially protected resources under uncertainty. *Journal of Environmental Economics and Management 59*, 129–141.

Hilborn, R., J. Orensanz, and A. Parma (2005). Institutions, incentives and the future of fisheries. *Philosophical Transactions of the Royal Society B 360*, 47–57.

Kaffine, D. and C. Costello (2011). Unitization of spatially connected renewable resources. *BE Journal of Economic Analysis and Policy (Contributions) 11*(1).

Kapaun, U. and M. Quaas (2013). Does the optimal size of a fish stock increase with environmental uncertainties? *Environmental and Resource Economics 54*, 21–39.

Kotchen, M. (2006). Green markets and private provision of public goods. *Journal of Political Economy 114*, 816–834.

Kotchen, M. (2009). Voluntary provision of public goods for bads: A theory of environmental offsets. *Economic Journal 119*, 883–899.

Libecap, G. and S. Wiggins (1985). The influence of private contractual failure on regulation: the case of oil field unitization. *Journal of Political Economy 93*, 690–714.

Mailath, G. J. and L. Samuelson (2006). *Repeated games and reputations: long-run relationships*. Oxford university press.

Marx, L. M. and S. A. Matthews (2000). Dynamic voluntary contribution to a public project. *The Review of Economic Studies 67*(2), 327–358.

Mas-Colell, A., M. Whinston, and J. Green (1995). *Microeconomic Theory*. Oxford University Press.

Maskin, E. and J. Tirole (1999). Two remarks on the property-rights literature. *Review of Economic Studies 66*, 139–149.

Nathan, R., G. G. Katul, H. S. Horn, S. M. Thomas, R. Oren, R. Avissar, S. W. Pacala, and S. A. Levin (2002). Mechanisms of long-distance dispersal of seeds by wind. *Nature 418*(6896), 409–413.

Ostrom, E. (1990). *Governing the Commons, the Evolution of Institutions for Collective Actions*. Cambridge University Press.

Reed, W. J. (1979). Optimal escapement levels in stochastic and deterministic harvesting models. *Journal of Environmental Economics and Management 6*, 350–363.

Samuelson, P. A. (1954). The pure theory of public expenditure. *Review of Economics and Statistics 36*, 387–389.

Sanchirico, J. and J. Wilen (2009). *Economically optimal management of a metapopulation*, Chapter 16, pp. 317–332. CRC Press.

Siegel, D., B. Kinlan, B. Gaylord, and S. Gaines (2003). Lagrangian descriptions of marine larval dispersion. *Marine Ecology Progress Series 260*, 83–96.

Tarui, N. (2007). Inequality and outside options in common-property resource use. *Journal of Development Economics 83*, 214–239.

Vicary, S. (2000). Donations to a public good in a large economy. *European Economic Review 44*, 609–618.

Wang, C. and G. Zudenkova (2016). Non-monotonic group-size effect in repeated provision of public goods. *European Economic Review 89*, 116–128.

White, C. and C. Costello (2014). Close the high seas to fishing? *PLoS biology 12*(3), e1001826.

Wilen, J. E., J. Cancino, and H. Uchida (2012). The economics of territorial use rights fisheries, or turfs. *Review of Environmental Economics and Policy 6*(2), 237–257.

World Resource Institute (2019). Water risk atlas. Technical report, `wri.org/aqueduct`.

Appendix

Proof of Proposition 1

We proceed by backward induction. We first consider the case where $g_i'(0) > \frac{1}{\delta D_{ii}}$. At final period $kT-1$, concessionaire i's problem is to maximize

$$\max_{e_{ikT-1}\geq 0} p_i\left(x_{ikT-1} - e_{ikT-1}\right)$$

Using the first order condition yields $\bar{e}_{ikT-1} = 0$: concessionaire i extracts the entire stock at the final period. Moving backward, at period $T-2$, this concessionaire's problem becomes:

$$\max_{e_{ikT-2}\geq 0} p_i \left[x_{ikT-2} - e_{ikT-2} + \delta\left(\sum_{j\neq i} D_{ji} g(\bar{e}_{jkT-2}) + D_{ii} g(e_{ikT-2}) - \bar{e}_{ikT-1}\right)\right].$$

Using the first order condition and $\bar{e}_{ikT-1} = 0$, we obtain that:

$$\delta D_{ii} g'(\bar{e}_{ikT-2}) = 1.$$

This is so since $\bar{e}_{ikT-2} = 0$ is ruled out by the lower bound on $g'(0)$, and $\bar{e}_{ikT-2} = x_{ikT-2}$ is ruled out if $x_{ikT-2} > (g')^{-1}\left(\frac{1}{\delta D_{ii}}\right)$ holds. Using again backward induction highlights that any $\bar{e}_{it}$ ($(k-1)T \leq t \leq kT-3$) is characterized by the same condition provided that $x_{it} > (g')^{-1}\left(\frac{1}{\delta D_{ii}}\right) = \bar{e}_i$. We have, by definition of $\bar{e}_i$ and concavity of $g(.)$:

$$g(\bar{e}_i) > \bar{e}_i g'(\bar{e}_i) = \frac{\bar{e}_i}{\delta D_{ii}}$$

which implies $D_{ii}g(\bar{e}_i) > \frac{\bar{e}_i}{\delta} \geq \bar{e}_i$ for $\delta \in]0,1]$, and we deduce that $x_{it} > \bar{e}_i$ for any tenure block but the first one. Even if concessionaire i chooses to defect at the beginning, since $x_{i0} > (g')^{-1}\left(\frac{p_i}{\delta \sum_j D_{ij}p_j}\right) > (g')^{-1}\left(\frac{1}{\delta D_{ii}}\right)$ by assumption, the same conclusion follows. The second case follows from backward induction arguments because of the upper bound on $g'(0)$.

Proof of Proposition 2

If there is t during which concessionaire i chooses $e_{it} > e_i^*$: e_{it} is strictly profitable only if:

$$p_i\left(1+\delta\right)\left(x_i^* - e_i^*\right) < p_i\left[\left(x_i^* - e_{it}\right) + \delta\left(\sum_{j\neq i} D_{ji}g\left(e_j^*\right) + D_{ii}g\left(e_{it}\right)\right)\right].$$

Simplifying this inequality, we obtain:

$$\delta D_{ii}\left(g\left(e_{it}\right) - g\left(e_i^*\right)\right) > e_{it} - e_i^*. \tag{22}$$

Since $g(.)$ is continuously differentiable and increasing, there exists $e_i \in]e_i^*, e_{it}[$ such that $g\left(e_{it}\right) - g\left(e_i^*\right) = \left(e_{it} - e_i^*\right)g'(e_i)$ and we rewrite expression 22 as follows:

$$\delta D_{ii}\left(e_{it} - e_i^*\right)g'(e_i) > e_{it} - e_i^* \Leftrightarrow g'(e_i) > \frac{1}{\delta D_{ii}} = g'(\bar{e}_i).$$

Since $g(.)$ is strictly concave we have $e_i^* < e_i < \bar{e}_i$, which is a contradiction (since $e_i^* \geq \bar{e}_i$ as explained in subsection 3.1.2). This implies that $e_{it} = e_i^*$ for any time period t.

Proof of Proposition 3

If concessionaire i deviates during tenure $k+1$ (while other concessionaires follow their equilibrium strategies) then this concessionaire's payoff is $\Pi_i^d = p_iA$, where :

$$A = \left[x_{i0} - e_i^* + \frac{\delta(1-\delta^{kT-1})}{1-\delta}\left(x_i^* - e_i^*\right) + \delta^{kT}\left(x_i^* - \bar{e}_i\right) + \frac{\delta^{kT+1}(1-\delta^{T-2})}{1-\delta}\left(\bar{x}_i - \bar{e}_i\right) + \delta^{(k+1)T-1}\bar{x}_i\right].$$

Now, using Condition (13), we compute $\Pi_i^c - \Pi_i^d = p_iB$, with:

$$B = \frac{\delta^{kT}p_i}{1-\delta}\left[\delta x_i^* - e_i^* - \left(1-\delta^{T-1}\right)\left(\delta\bar{x}_i - \bar{e}_i\right)\right] \tag{23}$$

The conclusion follows from Equality (23).

Proof of Proposition 4

We prove that the concessionaire does not defect from the initial period until the end of the first tenure. From the proof of Proposition 3 (using the expression (42) when $k = 0$) we know that:

$$\Pi_i^c - \Pi_i^d = \frac{p_i}{1-\delta}\left[\delta x_i^* - e_i^* - \left(1-\delta^{T-1}\right)\left(\delta \bar{x}_i - \bar{e}_i\right)\right]$$

When D_{ii} gets arbitrarily close to one, we deduce that $\bar{e}_i$ gets arbitrarily close to e_i^*, so that $\bar{x}_i$ gets arbitrarily close to x_i^*. We can deduce that $\Pi_i^c - \Pi_i^d$ gets arbitrarily close to:

$$\frac{p_i}{1-\delta}\left[\delta x_i^* - e_i^* - \left(1-\delta^{T-1}\right)\left(\delta x_i^* - e_i^*\right)\right] > 0 \tag{24}$$

Thus, for $D_{ii} = 1$ we know that $\Pi_i^c - \Pi_i^d > 0$ which, by a continuity argument, implies that this deviation is not profitable for sufficiently large (but less than one) values of self retention.

Proof of Proposition 5

Using Proposition 3, we know that concessionaire i would defect if the following condition is satisfied:

$$\delta x_i^* - e_i^* < \left(1-\delta^{T-1}\right)\left(\delta \bar{x}_i - \bar{e}_i\right).$$

The right hand side of this inequality increases as T increases: its derivative as a function of T is $-\delta^{T-1} ln(\delta)\left(\delta \bar{x}_i - \bar{e}_i\right)$, which is positive, since $ln(\delta) < 0$ and $\delta \bar{x}_i - \bar{e}_i$ is positive.[33] As such, for any tenure length T there will be defection if $\delta x_i^* - e_i^*$ is negative. Now, if D_{ii} is sufficiently small, then $\bar{e}_i = 0$ and we focus on cases where e_i^* is still positive. We examine the extreme case where $e_i^* > 0$ even when D_{ii} is equal to zero. Using the characterization of e_i^*, we can rewrite $\delta x_i^* - e_i^*$ as follows:

$$\delta x_i^* - e_i^* = \delta\left[\sum_{j\neq i} D_{ji} g(e_j^*) - \sum_{j\neq i} D_{ij}\frac{p_j}{p_i} g'(e_i^*) e_i^*\right].$$

When Condition 17 holds, then $\delta x_i^* - e_i^*$ is negative.

Proof of Proposition 6

We claim that, as T gets arbitrarily large, any concessionaire i will defect from cooperation. Assume that any concessionaire $j \neq i$ follows the cooperation path; we analyze concessionaire i's incentives to defect. One possible deviation is described in Proposition 1: he might deviate from the initial period until period T. Then this concessionaire will not be renewed. According to Proposition 1, his payoff from defecting will then be equal to Π_i^d. We now prove that $\Pi_i^c - \Pi_i^d \leq 0$ for sufficiently large values of T. Using the proof of proposition 3 (expression (42) when $k = 0$) we have:

$$\Pi_i^c - \Pi_i^d = \frac{\delta^{kT} p_i}{1-\delta}\left[\delta x_i^* - e_i^* - \left(1-\delta^{T-1}\right)\left(\delta \bar{x}_i - \bar{e}_i\right)\right].$$

[33] Indeed, $\delta \bar{x}_i - \bar{e}_i = \delta \sum_{j\neq i} D_{ji} g(e_j^*) + \delta D_{ii} g(\bar{e}_i) - \delta D_{ii} g'(\bar{e}_i)\bar{e}_i = \delta \sum_{j\neq i} D_{ji} g(e_j^*) + \delta D_{ii}\left(g(\bar{e}_i) - g'(\bar{e}_i)\bar{e}_i\right) > 0$ since the second term is positive by concavity of the growth function g. If $D_{ii} = 0$ then $\delta \bar{x}_i - \bar{e}_i = \delta \bar{x}_i$ is positive too.

When T gets large, the term between brackets in the right-hand side term gets close to

$$[\delta x_i^* - e_i^* - (\delta \bar{x}_i - \bar{e}_i)]\,. \tag{25}$$

Now, we obtain the following inequality $x_i^* - \bar{x}_i = D_{ii}(g(e_i^*) - g(\bar{e}_i)) < D_{ii}g'(\bar{e}_i)(e_i^* - \bar{e}_i)$ and this enables us to deduce the following inequality regarding Equation (25):

$$[\delta D_{ii}(g(e_i^*) - g(\bar{e}_i)) - (e_i^* - \bar{e}_i)] < \frac{p_i}{1-\delta}[\delta D_{ii}g'(\bar{e}_i) - 1](e_i^* - \bar{e}_i). \tag{26}$$

But we know that $\bar{e}_i$ satisfies $\delta D_{ii}g'(\bar{e}_i) = 1$, which implies that the right hand side of the above inequality is equal to zero. We conclude that (25) is negative which, by a continuity argument, implies that $\Pi_i^c - \Pi_i^d \leq 0$ for sufficiently large values of T.

Proof of Proposition 7

For a given concessionaire i, consider $\bar{T}_i$ defined implicitly by:

$$\bar{e}_i - e_i^* + \frac{\delta}{1-\delta}(x_i^* - e_i^*) - \frac{\delta(1-\delta^{\bar{T}_i - 1})}{1-\delta}(\bar{x}_i - \bar{e}_i) - \delta^{\bar{T}_i - 1}\bar{e}_i = 0.$$

Since $\bar{e}_i$ and e_i^* (and thus stock levels) do not depend on the value of the time horizon, we can differentiate the left hand side of the equality as a function of T, and we obtain:

$$\delta^{T-1}\frac{ln(\delta)}{1-\delta}\left(\delta\bar{x}_i - \bar{e}_i\right)$$

which is negative since $ln(\delta) < 0$ as $0 < \delta \leq 1$ and $\delta\bar{x}_i - \bar{e}_i$ is positive (as shown in the proof of Proposition 5). This implies that the left hand side of the equality is a decreasing and continuous function of T (where T is assumed to take continuous values). Since the proof of Proposition 2 implies that this function takes on negative values as T becomes large, if it has a positive value when $T = 2$ then $\bar{T}_i$ is uniquely defined and $\bar{T}_i > 1$.[34] Then, the proof of Proposition 4 implies that concessionaire i will have incentives to defect as soon as the renewal time horizon is larger than $\bar{T}_i$.

For $T = \mathbf{2}$ the value of the function is given by the following expression:

$$\bar{e}_i - e_i^* + \frac{\delta}{1-\delta}\left(x_i^* - e_i^*\right) - \delta\bar{x}_i = \frac{1}{1-\delta}\left[\delta x_i^* - e_i^* - (1-\delta)\left(\delta\bar{x}_i - \bar{e}_i\right)\right].$$

This expression is positive due to Assumption (19), which implies the existence and uniqueness of

$$\bar{T}_i = \mathbf{1} + \frac{ln\left[\frac{\delta\bar{x}_i - \bar{e}_i - (\delta x_i^* - e_i^*)}{\delta\bar{x}_i - \bar{e}_i}\right]}{ln(\delta)}.$$

This concludes the proof of the result since $\bar{T} = \min_i \bar{T}_i$ qualifies as the appropriate threshold value.

[34] Keep in mind that $\bar{T}_i$ is assumed to take continuous values in the proof. As it is actually discrete, the proof implies that $\bar{T}_i$ is at least equal to 2.

Proof of Proposition 8

First, during the final tenure block K, using backward induction reveals that any concessionaire i's strategy is characterized by $e_{i,KT-1} = 0$, and for any other period $(K-1)T \leq t \leq KT-2$ we have $e_{i,t} = \bar{e}_i$ where $1 = \delta D_{ii} g'(\bar{e}_i)$. Thus, anticipating that he will not get renewed at the end of the final tenure block, any concessionaire i will defect. In order to reach the final tenure block, all concessionaires will have cooperated (for the first $K-1$ tenure blocks). Thus, cooperative concessionaire i will play as follows (the first tenure block starting at $t=0$). During the first $K-1$ tenure blocks he chooses $e_i = e_i^*$: from $t=1$ to $t=(K-1)T-1$ the stock level is $x_i = x_i^*$, at period $t=0$ we have $x_i = x_{i,0}$. Then, at period $t=(K-1)T$, he chooses $e_i = \bar{e}_i$, and stock level at this same period $(K-1)T$ is still $x_i = x_i^*$. In all other periods of the final tenure block but the last one, he chooses $e_i = \bar{e}_i$ and the stock level is $\bar{\bar{x}}_i = \sum_j D_{ji} g(\bar{e_j})$. Finally, at $t = KT-1$ we have $e_i = 0$ and $x_i = \bar{\bar{x}}_i$. This implies that the payoffs from cooperation are this time given by:

$$\Pi_i^c = p_i \left[x_{i,0} - e_i^* + \sum_{t=1}^{(K-1)T-1} \delta^t (x_i^* - e_i^*) + \delta^{(K-1)T}(x_i^* - \bar{e}_i) + \sum_{t=(K-1)T+1}^{KT-2} \delta^t (\bar{\bar{x}}_i - \bar{e}_i) + \delta^{KT-1} \bar{\bar{x}}_i \right].$$

Now, we consider concessionaire i's potential unilateral deviation strategy. Assuming that this concessionaire defects during tenure block $1 \leq k < K$ (thus knowing that he will not be renewed following tenure block k) the timing of his strategy is as follows. From $t=0$ to $t=(k-1)T-1$ he chooses $e_i = e_i^*$: from $t=1$ to $t=(k-1)T-1$ the stock level is $x_i = x_i^*$, at period $t=0$ we have $x_i = x_{i,0}$. Then, at period $t=(k-1)T$, he defects by choosing $e_i = \bar{e}_i$, and the stock level at this same period $(k-1)T$ is still $x_i = x_i^*$. In all other periods of tenure block k but the last one, he chooses $e_i = \bar{e}_i$ and the stock level is $x_i = \bar{x}_i$. Finally, at $t = kT-1$ we have $e_i = 0$ and $x_i = \bar{x}_i$. This implies that the payoffs from defecting during tenure block $k < K$ are given by:

$$\Pi_i^d = p_i \left[x_{i,0} - e_i^* + \sum_{t=1}^{(k-1)T-1} \delta^t (x_i^* - e_i^*) + \delta^{(k-1)T}(x_i^* - \bar{e}_i) + \sum_{t=(k-1)T+1}^{kT-2} \delta^t (\bar{x}_i - \bar{e}_i) + \delta^{kT-1} \bar{x}_i \right].$$

Using the expressions of Π_i^c and Π_i^d, we obtain:

$$\Pi_i^c - \Pi_i^d = \frac{p_i \delta^{(k-1)T}}{1-\delta} \left\{ \left(1 - \delta^{(K-k)T}\right)(\delta x_i^* - e_i^*) + \delta^{(K-k)T}\left(1 - \delta^{T-1}\right)\delta \bar{\bar{x}}_i - \left(1 - \delta^{T-1}\right)\left[\delta \bar{x}_i - \left(1 - \delta^{(K-k)T}\right)\bar{e}_i\right]\right\}.$$

This implies that the sign of $\Pi_i^c - \Pi_i^d$ is given by that of:

$$\Phi(k) := \left(1 - \delta^{(K-k)T}\right)(\delta x_i^* - e_i^*) + \delta^{(K-k)T}\left(1 - \delta^{T-1}\right)\delta \bar{\bar{x}}_i - \left(1 - \delta^{T-1}\right)\left[\delta \bar{x}_i - \left(1 - \delta^{(K-k)T}\right)\bar{e}_i\right]$$

Differentiating $\Phi(\cdot)$ with respect to k, we obtain:

$$\Phi'(k) = \delta^{(K-k)T} T ln(\delta) \left\{ \delta x_i^* - e_i^* - \left(1 - \delta^{T-1}\right)\left[\delta \bar{\bar{x}}_i - \bar{e}_i\right]\right\}. \tag{27}$$

We have $\bar{\bar{x}}_i \leq \bar{x}_i$. If concessionaires cooperate in the infinite horizon problem:

$$\delta x_i^* - e_i^* > \left(1 - \delta^{T-1}\right)(\delta \bar{x}_i - \bar{e}_i), \tag{28}$$

Then we have:

$$\delta x_i^* - e_i^* - \left(1-\delta^{T-1}\right)\left[\delta\bar{\bar{x}}_i - \bar{e}_i\right] > \delta x_i^* - e_i^* - \left(1-\delta^{T-1}\right)\left(\delta\bar{x}_i - \bar{e}_i\right) > 0.$$

This implies that the term between brackets on the right hand side of Equality (27) is positive. Since $ln(\delta) < 0$ as $\delta \in (0,1]$ we have $\Phi'(k) < 0$ for any k. Thus willingness to cooperate is decreasing in k - the longer we wait to defect, the lower is their incentive to cooperate. This implies that $k = K-1$ corresponds to the lowest possible value of $\Phi(k)$. In other words, if concessionaire i will defect, she will have the strongest incentive to do so late in the game. We then obtain:

$$\Phi(K-1) = \left(1-\delta^T\right)\left(\delta x_i^* - e_i^*\right) + \delta^T\left(1-\delta^{T-1}\right)\delta\bar{\bar{x}}_i - \left(1-\delta^{T-1}\right)\left[\delta\bar{x}_i - \left(1-\delta^T\right)\bar{e}_i\right].$$

The reasoning above implies that $\Phi(K-1) > 0$ is necessary and sufficient to ensure that concessionaire i will not defect. This condition can be rewritten as follows:

$$\delta x_i^* - e_i^* > \frac{1-\delta^{T-1}}{1-\delta^T}\left\{\delta\bar{x}_i - \left(1-\delta^T\right)\bar{e}_i - \delta^{T+1}\bar{\bar{x}}_i\right\}.$$

This concludes the proof of the first part of the proposition. Finally, we show that Condition 20 is more stringent than Condition (28). Indeed, we have:

$$\frac{1-\delta^{T-1}}{1-\delta^T}\left[\delta\bar{x}_i - \left(1-\delta^T\right)\bar{e}_i - \delta^{T+1}\bar{\bar{x}}_i\right] - \left(1-\delta^{T-1}\right)\left(\delta\bar{x}_i - \bar{e}_i\right) = \frac{1-\delta^{T-1}}{1-\delta^T}\delta^{T+1}\left(\bar{x}_i - \bar{\bar{x}}_i\right) > 0.$$

This inequality implies that, as soon as Condition 20 is satisfied then Condition 28 is satisfied:

$$\delta x_i^* - e_i^* > \frac{1-\delta^{T-1}}{1-\delta^T}\left[\delta\bar{x}_i - \left(1-\delta^T\right)\bar{e}_i - \delta^{T+1}\bar{\bar{x}}_i\right] \Rightarrow \delta x_i^* - e_i^* > \left(1-\delta^{T-1}\right)\left(\delta\bar{x}_i - \bar{e}_i\right),$$

but the opposite does not always hold true. Full cooperation under the infinite horizon instrument is not sufficient to ensure the same result under the finite horizon version of the instrument.

Proof of Proposition 9

Negative density-dependent dispersal implies that $D'(.) < 0$ holds, and we conclude from (21) that $g_i'(\hat{e}_i) > g_i'(\bar{e}_i)$ which, due to concavity of the growth function, allows to conclude the proof.

Sections 4.2 and 4.3

We have the following stocks, respectively, when patch i defects and when all patches cooperate:

$$\bar{x}_i = D_{ii}g\left(\bar{e}_i, \alpha_i\right) + \sum_{j\neq i} D_{ji}g\left(e_j^*, \alpha_j\right); \quad x_i^* = \sum_j D_{ji}g\left(e_j^*, \alpha_j\right)$$

We assume that one parameter, $\theta_i = \{p_i, \alpha_i, D_{ii}, D_{ij}\}$ or $\theta_j = \{p_j, \alpha_j, D_{ji}\}$, is elevated. We obtain:

$$\frac{d\bar{x}_i}{d\theta_i} = \frac{\partial \bar{x}_i}{\partial \bar{e}_i} \cdot \frac{\partial \bar{e}_i}{\partial \theta_i} + \frac{\partial \bar{x}_i}{\partial \theta_i} + \sum_{j \neq i} \frac{\partial \bar{x}_i}{\partial e_j^*} \cdot \frac{\partial e_j^*}{\partial \theta_i} \tag{29}$$

$$\frac{d\bar{x}_i}{d\theta_j} = \frac{\partial \bar{x}_i}{\partial \theta_j} + \sum_{l \neq i} \frac{\partial \bar{x}_i}{\partial e_l^*} \cdot \frac{\partial e_l^*}{\partial \theta_j} \tag{30}$$

$$\frac{dx_i^*}{d\theta_i} = \frac{\partial x_i^*}{\partial \theta_i} + \sum_{j} \frac{\partial x_i^*}{\partial e_j^*} \cdot \frac{\partial e_j^*}{\partial \theta_i} \tag{31}$$

$$\frac{dx_i^*}{d\theta_j} = \frac{\partial x_i^*}{\partial \theta_j} + \sum_{l} \frac{\partial x_i^*}{\partial e_l^*} \cdot \frac{\partial e_l^*}{\partial \theta_j} \tag{32}$$

and the residual stock levels

Table 2: Computations of derivatives

θ	$\frac{\partial e_i^*}{\partial \theta}$	$\frac{\partial \bar{e}_i}{\partial \theta}$	$\frac{\partial x_i^*}{\partial \theta}$	$\frac{\partial \bar{x}_i}{\partial \theta}$
p_i	$\frac{1-\delta D_{ii} g_{e_i}}{\sum_{j=1}^{N} \delta D_{ij} p_j g_{e_i e_i}} < 0$	0	0	0
p_j	$-\frac{D_{ij} g_{e_i}}{\sum_{l=1}^{N} D_{il} p_l g_{e_i e_i}} > 0$	0	0	0
α_i	$-\frac{g_{e_i \alpha_i}}{g_{e_i e_i}} > 0$	$-\frac{g_{e_i \alpha_i}}{g_{e_i e_i}} > 0$	$D_{ii} g_{\alpha_i^*} > 0$	$D_{ii} g_{\bar{\alpha}_i} > 0$
α_j	0	0	$D_{ji} g_{\alpha_j^*} > 0$	$D_{ji} g_{\alpha_j^*} > 0$
D_{ii}	$-\frac{p_i g_{e_i}}{\sum_{j=1}^{N} D_{ij} p_j g_{e_i e_i}} > 0$	$-\frac{g_{e_i}}{g_{e_i e_i}} > 0$	$g(e_i^*) > 0$	$g(\bar{e}_i) > 0$
D_{ij}	$-\frac{p_j g_{e_i}}{\sum_{j=1}^{N} D_{ij} p_j g_{e_i e_i}} > 0$	0	0	0
D_{ji}	0	0	$g(e_j^*)$	$g(e_j^*)$

with $g_{\alpha_i^*} \equiv g_{\alpha_i}(e_i^*)$ and $g_{\bar{\alpha}_i} \equiv g_{\bar{\alpha}_i}(\bar{e}_i)$.

A. Impact on the emergence of cooperation

Using Expressions (29) to (32) and Table 1 we compute the following expressions.

Impact of net price, p

Impact of p_i

We first analyze the impact of p_i on concessionaire i's willingness to cooperate by using Expressions (29) to (32) and the table in order to obtain:

$$\begin{aligned}\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{dp_i} &= \frac{\delta^{kT}}{1-\delta}\left[\delta x_i^* - e_i^* - (1-\delta^{T-1})(\delta\bar{x}_i - \bar{e}_i)\right] \\ &\quad + \frac{\delta^{kT}p_i}{1-\delta}\left[\delta\sum_j \frac{\partial x_i^*}{\partial e_j^*}\frac{\partial e_j^*}{\partial p_i} - \frac{\partial e_i^*}{\partial p_i} - \delta(1-\delta^{T-1})\sum_{j\neq i}\frac{\partial \bar{x}_i}{\partial e_j^*}\frac{\partial e_j^*}{\partial p_i}\right]\end{aligned}$$

Let us focus on the second term between brackets and rewrite it as follows:

$$\frac{\partial e_i^*}{\partial p_i}\left(\delta D_{ii}g_{e_i^*}-1\right) + \sum_{j\neq i}\frac{\partial e_j^*}{\partial p_i}\left[\delta D_{ji}g_{e_j^*} - \delta(1-\delta^{T-1})D_{ji}g_{e_j^*}\right] \tag{33}$$

$$\Leftrightarrow\ -\frac{\partial e_i^*}{\partial p_i}\left(1-\delta D_{ii}g_{e_i^*}\right) + \sum_{j\neq i}\frac{\partial e_j^*}{\partial p_i}\delta^T D_{ji}g_{e_j^*} > 0 \tag{34}$$

because we have $\frac{\partial e_i^*}{\partial p_i} < 0$, $1-\delta D_{ii}g_{e_i^*} > 0$ and $\frac{\partial e_j^*}{\partial p_i} > 0$. Thus $\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{dp_i} > 0$ if the condition regarding concessionaire i's *willingness-to-cooperate* is satisfied. So, an increase in p_i results in an increase in the value of $\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{dp_i}$, thus an increase in the *willingness-to-cooperate*.

Effect of p_j, $j \neq i$

In this case we have

$$\begin{aligned}\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{dp_j} &= \frac{\delta^{kT}p_i}{1-\delta}\left[\delta\sum_l \frac{\partial x_i^*}{\partial e_l^*}\frac{\partial e_l^*}{\partial p_j} - \frac{\partial e_i^*}{\partial p_j} - \delta(1-\delta^{T-1})\sum_{l\neq i}\frac{\partial \bar{x}_i}{\partial e_l^*}\frac{\partial e_l^*}{\partial p_j}\right] \\ &= \frac{\delta^{kT}p_i}{1-\delta}\left[\underbrace{-\frac{\partial e_i^*}{\partial p_j}\left(1-\delta D_{ii}g_{e_i^*}\right)}_{<0} + \delta^T\left(\underbrace{\frac{\partial e_j^*}{\partial p_j}D_{ji}g_{e_j^*}}_{<0} + \underbrace{\sum_{l\neq i,j}\frac{\partial e_l^*}{\partial p_j}D_{li}g_{e_l^*}}_{>0}\right)\right]\end{aligned}$$

Focusing on the spatial connection between the patch of interest and the patch where the value of the parameter is increased, (i and j), we deduce the following conclusions. First, if both dispersal rates D_{ij} and D_{ji} are small, then the first and second term between brackets on the RHS of the equality are small, which implies that $\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{dp_j}$ is positive. Indeed, when D_{ij} and D_{ji} are small, then $\frac{\partial e_i^*}{\partial p_j}$ and $\frac{\partial e_j^*}{\partial p_j}D_{ji}g_{e_j^*}$ are small. And the sign of the term between brackets (and thus of $\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{dp_j}$) is similar to the sign of $\sum_{l\neq i,j}\frac{\partial e_l^*}{\partial p_j}D_{li}g_{e_l^*}$, which is positive. Second, if the degree of spatial connection between the two patches and their own self-retention rate are large (or if both patches i and j are weakly spatially-connected with others), respectively $D_{ii}+D_{ij}$ and $D_{jj}+D_{ji}$ are large, then the term $\sum_{l\neq i,j}\frac{\partial e_l^*}{\partial p_j}D_{li}g_{e_l^*}$ is small, which implies that $\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{dp_j}$ is negative.

Impact of growth, α

Effect of α_i

We analyze the effect of α_i on concessionaire i's willingness to cooperate. We have:

$$\begin{aligned}
\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{d\alpha_i} &= \frac{\delta^{kT}p_i}{1-\delta}\left\{\delta\left(\frac{\partial x_i^*}{\partial\alpha_i}+\frac{\partial x_i^*}{\partial e_i^*}\frac{\partial e_i^*}{\partial\alpha_i}\right)-\frac{\partial e_i^*}{\partial\alpha_i}-(1-\delta^{T-1})\left[\delta\left(\frac{\partial\bar{x}_i}{\partial\alpha_i}+\frac{\partial\bar{x}_i}{\partial\bar{e}_i}\frac{\partial\bar{e}_i}{\partial\alpha_i}\right)-\frac{\partial\bar{e}_i}{\partial\alpha_i}\right]\right\}\\
&= \frac{\delta^{kT}p_i}{1-\delta}\left[\frac{\partial e_i^*}{\partial\alpha_i}\left(\delta D_{ii}g_{e_i^*}-1\right)+\delta D_{ii}g_{\alpha_i^*}-(1-\delta^{T-1})\left(\frac{\partial\bar{e}_i}{\partial\alpha_i}\left(\delta D_{ii}g_{\bar{e}_i}-1\right)+\delta D_{ii}g_{\bar{\alpha}_i}\right)\right]\\
&= \frac{\delta^{kT}p_i}{1-\delta}\left[\frac{\partial e_i^*}{\partial\alpha_i}\left(\delta D_{ii}g_{e_i^*}-1\right)+\delta D_{ii}\left(g_{\alpha_i^*}-(1-\delta^{T-1})g_{\bar{\alpha}_i}\right)\right]
\end{aligned}$$

If D_{ii} is small while $\bar{e}_i>0$, then $\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{d\alpha_i}<0$ holds. If $D_{ii}=1$, then $1-\delta D_{ii}g_{e_i^*}=0$ and $\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{d\alpha_i}>0$ since $g_{\alpha_i^*}-(1-\delta^{T-1})g_{\bar{\alpha}_i}$ is positive. By a continuity argument, this conclusion remains valid when D_{ii} is large.

Effect of α_j, $j\neq i$

We analyze the effect of α_j on concessionaire i's willingness to cooperate. We have:

$$\begin{aligned}
\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{d\alpha_j} &= \frac{\delta^{kT}p_i}{1-\delta}\left[\delta\left(\frac{\partial x_i^*}{\partial\alpha_j}+\frac{\partial x_i^*}{\partial e_j^*}\frac{\partial e_j^*}{\partial\alpha_j}\right)-\delta(1-\delta^{T-1})\left(\frac{\partial\bar{x}_i}{\partial\alpha_j}+\frac{\partial\bar{x}_i}{\partial e_j^*}\frac{\partial e_j^*}{\partial\alpha_j}\right)\right]\\
&= \frac{\delta^{(k+1)T}p_i}{1-\delta}D_{ji}\left(g_{\alpha_j^*}+g_{e_j^*}\right)>0
\end{aligned}$$

Impact of dispersal rate, D

Effect of D_{ii}

We have:

$$\begin{aligned}
\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{dD_{ii}} &= \frac{\delta^{kT}p_i}{1-\delta}\left\{\delta\left(\frac{\partial x_i^*}{\partial D_{ii}}+\frac{\partial x_i^*}{\partial e_i^*}\frac{\partial e_i^*}{\partial D_{ii}}\right)-\frac{\partial e_i^*}{\partial D_{ii}}-(1-\delta^{T-1})\left[\delta\left(\frac{\partial\bar{x}_i}{\partial D_{ii}}+\frac{\partial\bar{x}_i}{\partial\bar{e}_i}\frac{\partial\bar{e}_i}{\partial D_{ii}}\right)-\frac{\partial\bar{e}_i}{\partial D_{ii}}\right]\right\}\\
&= \frac{\delta^{kT}p_i}{1-\delta}\left(\delta[g(e_i^*,\alpha_i)-g(\bar{e}_i,\alpha_i)]+\delta^T g(\bar{e}_i,\alpha_i)-\left(1-\delta D_{ii}g_{e_i^*}\right)\frac{\partial e_i^*}{\partial D_{ii}}\right).
\end{aligned}$$

The effect of D_{ii} on $\Pi_i^c-\Pi_i^d$ is given by the sum of two terms of opposite signs, and is thus ambiguous (due to the expression of $\frac{\partial e_i^*}{\partial D_{ii}}$, when p_i is small we might expect $\frac{d\left(\Pi_i^c-\Pi_i^d\right)}{dD_{ii}}$ to be positive).

Effect of D_{ij}

We have:

$$\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{dD_{ij}} = \frac{\delta^{kT} p_i}{1-\delta}\left(\delta \frac{\partial x_i^*}{\partial e_i^*}\frac{\partial e_i^*}{\partial D_{ij}} - \frac{\partial e_i^*}{\partial D_{ij}}\right) = -\frac{\delta^{kT} p_i}{1-\delta} \cdot \frac{\partial e_i^*}{\partial D_{ij}}\left(1-\delta D_{ii} g_{e_i^*}\right) < 0$$

Effect of D_{ji}

We have:

$$\begin{aligned}\frac{d\left(\Pi_i^c - \Pi_i^d\right)}{dD_{ji}} &= \frac{\delta^{kT} p_i}{1-\delta}\left[\delta\left(\frac{\partial x_i^*}{\partial D_{ji}} + \frac{\partial x_i^*}{\partial e_j^*}\frac{\partial e_j^*}{\partial D_{ji}}\right) - \delta(1-\delta^{T-1})\left(\frac{\partial \bar{x}_i}{\partial D_{ji}} + \frac{\partial \bar{x}_i}{\partial e_j^*}\frac{\partial e_j^*}{\partial D_{ji}}\right)\right] \\ &= \frac{\delta^{(k+1)T} p_i}{1-\delta}\left[\frac{\partial e_j^*}{\partial D_{ji}} D_{ji} g_{e_j^*} + g(e_j^*, \alpha_j)\right] > 0\end{aligned}$$

B. Impact on the time threshold, $\bar{T}_i$

Differentiating Condition (18) with respect to parameter θ, we have:

$$\frac{d\bar{T}_i}{d\theta} = \frac{\partial \bar{T}_i}{\partial \theta} + \frac{\partial \bar{T}_i}{\partial \bar{x}_i}\frac{d\bar{x}_i}{d\theta} + \frac{\partial \bar{T}_i}{\partial \bar{e}_i}\frac{\partial \bar{e}_i}{\partial \theta} + \frac{\partial \bar{T}_i}{\partial x_i^*}\frac{dx_i^*}{d\theta} + \frac{\partial \bar{T}_i}{\partial e_i^*}\frac{\partial e_i^*}{\partial \theta} \tag{35}$$

$$= \frac{1}{\ln(\delta)\left[\delta(\bar{x}_i - x_i^*) + e_i^* - \bar{e}_i\right]}\left[\frac{\partial e_i^*}{\partial \theta} - \delta\frac{dx_i^*}{d\theta} + \left(\frac{\delta x_i^* - e_i^*}{\delta \bar{x}_i - \bar{e}_i}\right)\left(\delta\frac{d\bar{x}_i}{d\theta} - \frac{\partial \bar{e}_i}{\partial \theta}\right)\right] \tag{36}$$

Since $\delta \in (0,1)$ and $\delta(\bar{x}_i - x_i^*) + e_i^* - \bar{e}_i > 0$, the first term in Equality (36) is always negative. Thus, in order to sign the effect of parameter θ on $\bar{T}_i$ we examine the term between brackets. Using (29)-(32) and Table 1, we have $\delta\frac{d\bar{x}_i}{d\theta} - \frac{\partial \bar{e}_i}{\partial \theta} \geqslant 0$. Notice that:

$$\begin{aligned}\frac{\partial e_i^*}{\partial \theta} - \delta\frac{dx_i^*}{d\theta} = \frac{\partial e_i^*}{\partial \theta}(1-\delta D_{ii} g_{e_i^*}) - \delta\left(\frac{\partial x_i^*}{\partial \theta} + \sum_{j\neq i} D_{ji} g_{e_j^*}\frac{\partial e_j^*}{\partial \theta}\right) &< 0 \text{ if } \theta = \{p_i; \alpha_j; D_{ji}\} \\ &> 0 \text{ if } \theta = \{D_{ij}\}\end{aligned}$$

which implies that $\frac{d\bar{T}_i}{d\theta} > 0$ for $\theta = \{p_i; \alpha_j; D_{ji}\}$ and $\frac{d\bar{T}_i}{d\theta} < 0$ for $\theta = \{D_{ij}\}$. By contrast, the sign is ambiguous for $\theta = \{p_j; \alpha_i; D_{ii}\}$. We can yet find cases highlighting that the overall expression can be positive or negative. We focus on the expression between brackets in Condition (36).

Effect of p_j, $j \neq i$

$$\frac{\partial e_i^*}{\partial p_j}\left(1 - \delta\frac{\partial x_i^*}{\partial e_i^*}\right) - \delta\sum_{l\neq i}\frac{\partial x_i^*}{\partial e_l^*}\frac{\partial e_l^*}{\partial p_j} + \delta\left(\frac{\delta x_i^* - e_i^*}{\delta \bar{x}_i - \bar{e}_i}\right)\sum_{l\neq i}\frac{\partial \bar{x}_i}{\partial e_l^*}\frac{\partial e_l^*}{\partial p_j} \tag{37}$$

$$\Leftrightarrow \frac{\partial e_i^*}{\partial p_j}(1-\delta D_{ii} g_{e_i}) + \delta\left(\frac{\delta(x_i^* - \bar{x}_i) - e_i^* + \bar{e}_i}{\delta \bar{x}_i - \bar{e}_i}\right)\left(D_{ji} g_{e_j}\frac{\partial e_j^*}{\partial p_j} + \sum_{l\neq i,j} D_{li} g_{e_l}\frac{\partial e_l^*}{\partial p_j}\right) \tag{38}$$

We now highlight that the effect on $\bar{T}_i$ depends on the dispersal process. First, if D_{ij} is small enough, then expression (36) is negative, which implies that the value of $\bar{T}_i$ increases when p_j increases. Second, if D_{ji} and $\sum_{l\neq i,j} D_{li}D_{lj}$ are small enough, then expression (36) is positive, which implies that $\bar{T}_i$ decreases when p_j increases. Indeed, this leads to a small value of the last term between brackets, $D_{ji}g_{e_j}\frac{\partial e_j^*}{\partial p_j} + \sum_{l\neq i,j} D_{li}g_{e_l}\frac{\partial e_l^*}{\partial p_j}$. Thus, the sign of $\frac{d\bar{T}_i}{dp_j}$ depends only on that of $\frac{\partial e_i^*}{\partial p_j}(1-\delta D_{ii}g_{e_i})$, which is positive. We thus conclude that $\frac{\partial \bar{T}_i}{\partial p_j}$ is negative.

Effect of α_i

$$\frac{\partial e_i^*}{\partial \alpha_i}\left(1-\delta\frac{\partial x_i^*}{\partial e_i^*}\right) - \delta\frac{\partial x_i^*}{\partial \alpha_i} + \left(\frac{\delta x_i^* - e_i^*}{\delta \bar{x}_i - \bar{e}_i}\right)\left[\delta\left(\frac{\partial \bar{x}_i}{\partial \alpha_i} + \frac{\partial \bar{x}_i}{\partial \bar{e}_i}\frac{\partial \bar{e}_i}{\partial \alpha_i}\right) - \frac{\partial \bar{e}_i}{\partial \alpha_i}\right] \tag{39}$$

$$\Leftrightarrow \frac{\partial e_i^*}{\partial \alpha_i}\left(1-\delta D_{ii}g_{e_i^*}\right) - \delta D_{ii}\left[g_{\alpha_i^*} - g_{\bar{\alpha}_i}\left(\frac{\delta x_i^* - e_i^*}{\delta \bar{x}_i - \bar{e}_i}\right)\right] \tag{40}$$

So, if δD_{ii} is sufficiently small while $\bar{e}_i$ remains positive, then the sign of (37) is positive, which implies that $\bar{T}_i$ would decrease when the growth-related parameter increases in patch i.

Effect of D_{ii}

$$\frac{\partial e_i^*}{\partial D_{ii}}\left(1-\delta\frac{\partial x_i^*}{\partial e_i^*}\right) - \delta\frac{\partial x_i^*}{\partial D_{ii}} + \left(\frac{\delta x_i^* - e_i^*}{\delta \bar{x}_i - \bar{e}_i}\right)\left[\delta\left(\frac{\partial \bar{x}_i}{\partial D_{ii}} + \frac{\partial \bar{x}_i}{\partial \bar{e}_i}\frac{\partial \bar{e}_i}{\partial D_{ii}}\right) - \frac{\partial \bar{e}_i}{\partial D_{ii}}\right]$$

$$\Leftrightarrow \frac{\partial e_i^*}{\partial D_{ii}}\left(1-\delta D_{ii}g_{e_i^*}\right) - \delta\underbrace{\left[g(e_i^*,\alpha_i) - \left(\frac{\delta x_i^* - e_i^*}{\delta \bar{x}_i - \bar{e}_i}\right)g(\bar{e}_i,\alpha_i)\right]}_{>0}$$

If δ is sufficiently small (so that $\frac{\partial e_i^*}{\partial D_{ii}}\left(1-\delta D_{ii}g_{e_i^*}\right) > \delta\left[g(e_i^*,\alpha_i) - \left(\frac{\delta x_i^* - e_i^*}{\delta \bar{x}_i - \bar{e}_i}\right)g(\bar{e}_i,\alpha_i)\right]$) while $\bar{e}_i$ remains positive, then the sign of the expression is that of $\frac{\partial e_i^*}{\partial D_{ii}}$, which is positive.

The scope of applicability of trigger strategies

Concessionaires implementing trigger strategies will not get renewed at the end of the tenure block where punishment is implemented. This is a form of self-punishment, which can be seen as an additional incentive scheme.[35] We only briefly consider this possibility.

Proposition 10. *When concessionaires follow trigger strategies, cooperation will emerge as an equilibrium outcome if and only if the following condition holds (for any concessionaire i):*

$$\delta x_i^* - e_i^* - (1-\delta^{T-1})\left[\delta\bar{\bar{x}}_i - \bar{e}_i\right] > 0,$$

where $\bar{\bar{x}}_i = \sum_j D_{ji}g(\bar{e_j}) > \bar{e}_i > 0$.

[35] The instrument analyzed here does not require that the concessionaires use such kind of self-punishment devices in order to induce efficient resource management.

Proof. If concessionaire i deviates during tenure $k+1$ (while other concessionaires follow trigger strategies) then this concessionaire's payoff is Π_i^d, where :

$$p_i \left[x_{i0} - e_i^* + \frac{\delta(1-\delta^{kT})}{1-\delta}\left(x_i^* - e_i^*\right) + \delta^{kT}\left(e_i^* - \bar{e}_i\right) + \frac{\delta^{kT+1}(1-\delta^{T-1})}{1-\delta}\left(\bar{\bar{x}}_i - \bar{e}_i\right) + \delta^{(k+1)T-1}\bar{e}_i \right].$$

Now, computing the difference $\Pi_i^c - \Pi_i^d$, we obtain:

$$\begin{aligned}\Pi_i^c - \Pi_i^d &= p_i \left[\frac{\delta^{kT+1}}{1-\delta}\left(x_i^* - e_i^*\right) - \delta^{kT}\left(e_i^* - \bar{e}_i\right) - \frac{\delta^{kT+1}(1-\delta^{T-1})}{1-\delta}\left(\bar{\bar{x}}_i - \bar{e}_i\right) - \delta^{(k+1)T-1}(1-\delta)\bar{e}_i \right] \\ &= \delta^{kT}\frac{p_i}{1-\delta}\left[\delta x_i^* - e_i^* - (1-\delta^{T-1})\left(\delta\bar{\bar{x}}_i - \bar{e}_i\right)\right].\end{aligned}$$

The conclusion follows. Condition $\bar{\bar{x}}_i = \sum_j D_{ji} g(\bar{e_j}) > \bar{e}_i$ follows from the same argument than in the proof of Proposition 1. □

The proof confirms one previous claim regarding the incentives to defect: it is straightforward to show that incentives to defect are the same at any given period. This proposition implies that the incentives to defect increase with a longer time horizon.[36] Moreover, the inequality characterizing the scope of trigger strategies is less restrictive than the similar condition in Proposition 3. Thus, using trigger strategies in addition to the concession instrument enlarges the scope for cooperation.

The case of stock-dependent costs

We obtain the following properties.[37]

Proposition 11. *The best defection strategy of concessionaire i in tenure block k is given by:*

$$\bar{e}_{ikT-1} = c_i^{-1}(p_i)$$

and, for any period $(k-1)T \leq t \leq kT-2$, we have $\bar{e}_{it} = \bar{e}_i > 0$ where:

$$\delta D_{ii} g_i'(\bar{e}_i)\left(p_i - c_i(\bar{x}_{it+1})\right) = p_i - c_i(\bar{e}_{it}) \quad \textit{with} \quad \bar{x}_{it} > \bar{e}_{it}.$$

Indeed $\bar{e}_{it} = \bar{e}_i$ since the system of optimality conditions is time and state independent.

Proof. We proceed by backward induction. At final period $kT-1$, concessionaire i's problem is to maximize

$$\max_{e_{ikT-1}\geq 0} p_i\left(x_{ikT-1} - e_{ikT-1}\right) - \int_{e_{ikT-1}}^{x_{ikT-1}} c_i(s)ds$$

[36] This conclusion follows if we differentiate the expression of the difference between payoffs as a function of the time horizon.

[37] To keep the exposition as simple as possible, we focus on the case of an interior best defection strategy. In Proposition 1 this corresponds to the case where the value of $g_i'(0)$ is high enough.

Using the first order condition enables us to conclude immediately that $c_i(\bar{e}_{ikT-1}) = p_i$, that is, concessionaire i extracts the stock up to level $\bar{e}_{ikT-1} = c_i^{-1}(p_i)$. Now, moving backward, at period $T-2$, this concessionaire's problem becomes:

$$\max_{e_{ikT-2}\geq 0} p_i\left[x_{ikT-2} - e_{ikT-2}\right] - \int_{e_{ikT-2}}^{x_{ikT-2}} c_i(s)ds + \delta p_i \left(\sum_{j\neq i} D_{ji}g(\bar{e}_{jkT-2}) + D_{ii}g(\bar{e}_{ikT-2}) - \bar{e}_{ikT-1}\right)$$

$$-\delta \int_{\bar{e}_{ikT-1}}^{\sum_{j\neq i} D_{ji}g(\bar{e}_{jkT-2})+D_{ii}g(\bar{e}_{ikT-2})} c_i(s)ds.$$

Using the first order condition (with respect to $\bar{e}_{ikT-2}$) and $\bar{e}_{ikT-1} = c_i^{-1}(p_i)$, we obtain that $\bar{e}_{ikT-2}$ is characterized by the following condition:

$$\delta D_{ii}g'(\bar{e}_{ikT-2})\left(p_i - c_i(\sum_{j\neq i} D_{ji}g(\bar{e}_{jkT-2}) + D_{ii}g(\bar{e}_{ikT-2}))\right) = p_i - c_i(\bar{e}_{ikT-2}).$$

This optimality condition enables quickly to deduce, since economic returns and spatial parameters are time independent, that $\bar{e}_{ikT-2}$ depends only on $\bar{e}_{jkT-2}$ $(j \neq i)$ and not on $\bar{x}_{lkT-2}$ $(l \in I)$. This implies that $\bar{e}_{ikT-2}$ is time and state independent. Repeating the same argument of backward induction, it is easily checked that any residual stock level $\bar{e}_{it}$ (where $(k-1)T \leq t \leq kT-3$) is characterized by the same optimality condition. This concludes the proof. □

Notice that, due to the analysis provided in Costello and Polasky (2008), the socially optimal policy remains time and state independent under stock-dependent costs. As such, we still denote by e_i^* and x_i^* the socially optimal residual stock level (stock level, respectively). Now we have:

Proposition 12. *Cooperation emerges as an equilibrium outcome if and only if, for any concessionaire i, the following condition holds:*

$$\frac{\delta^{kT+1}}{1-\delta}\left[p_i\left(x_i^* - e_i^*\right) - \int_{e_i^*}^{x_i^*} c_i(s)ds\right] - \delta^{kT}\left[p_i\left(e_i^* - \bar{e}_i\right) - \int_{\bar{e}_i}^{e_i^*} c_i(s)ds\right]$$

$$-\frac{\delta^{kT+1}(1-\delta^{T-2})}{1-\delta}\left[p_i\left(\bar{x}_i - \bar{e}_i\right) - \int_{\bar{e}_i}^{\bar{x}_i} c_i(s)ds\right] - \delta^{(k+1)T-1}\left[p_i\left(\bar{x}_i - c_i^{-1}(p_i)\right) - \int_{c_i^{-1}(p_i)}^{\bar{x}_i} c_i(s)ds\right] > 0. \tag{41}$$

Proof. If concessionaire i deviates during tenure $k+1$ (while other concessionaires follow their candidate equilibrium strategies) then this concessionaire's payoff is :

$$\Pi_i^d = p_i\left[x_{i0} - e_i^*\right] - \int_{e_i^*}^{x_{i0}} c_i(s)ds + \frac{\delta(1-\delta^{kT-1})}{1-\delta}\left[p_i\left(x_i^* - e_i^*\right) - \int_{e_i^*}^{x_i^*} c_i(s)ds\right]$$

$$+\delta^{kT}\left[p_i\left(x_i^* - \bar{e}_i\right) - \int_{\bar{e}_i}^{x_i^*} c_i(s)ds\right] + \frac{\delta^{kT+1}(1-\delta^{T-2})}{1-\delta}\left[p_i\left(\bar{x}_i - \bar{e}_i\right) - \int_{\bar{e}_i}^{\bar{x}_i} c_i(s)ds\right]$$

$$+\delta^{(k+1)T-1}\left[p_i\left(\bar{x}_i - c_i^{-1}(p_i)\right) - \int_{c_i^{-1}(p_i)}^{\bar{x}_i} c_i(s)ds\right].$$

Now we can compute $\Pi_i^c - \Pi_i^d = B$, with:

$$B = \frac{\delta^{kT+1}}{1-\delta}\left[p_i\left(x_i^* - e_i^*\right) - \int_{e_i^*}^{x_i^*} c_i(s)ds\right] - \delta^{kT}\left[p_i\left(e_i^* - \bar{e}_i\right) - \int_{\bar{e}_i}^{e_i^*} c_i(s)ds\right]$$

$$-\frac{\delta^{kT+1}(1-\delta^{T-2})}{1-\delta}\left[p_i\left(\bar{x}_i - \bar{e}_i\right) - \int_{\bar{e}_i}^{\bar{x}_i} c_i(s)ds\right] - \delta^{(k+1)T-1}\left[p_i\left(\bar{x}_i - c_i^{-1}(p_i)\right) - \int_{c_i^{-1}(p_i)}^{\bar{x}_i} c_i(s)ds\right]. \tag{42}$$

The conclusion follows from Equality (42). □

Proposition 12 yields several insights about the qualitative differences driven by the assumption of stock dependent costs. Indeed, using the proof of Proposition 3, it is easily checked that the first three terms on the left-hand side in condition (41) are formally equivalent to those in the case where costs do not depend on stock levels. The qualitative difference between both cases relates to the fourth term. When costs are stock independent, an agent who would choose to deviate would eventually drive the resource to extinction in his own patch. By contrast, if costs do depend on stock levels, agent i does not drive the resource to extinction if he chooses to defect, but he harvests it down to level $c_i^{-1}(p_i) > 0$. As highlighted by the fourth term on the left-hand side in condition (41), this has a negative effect on this agent's incentives to defect. As such, an interesting conclusion is that the assumption of stock-dependent costs, through its positive effect on cooperation incentives, would make cooperation easier to sustain from a qualitative point of view.